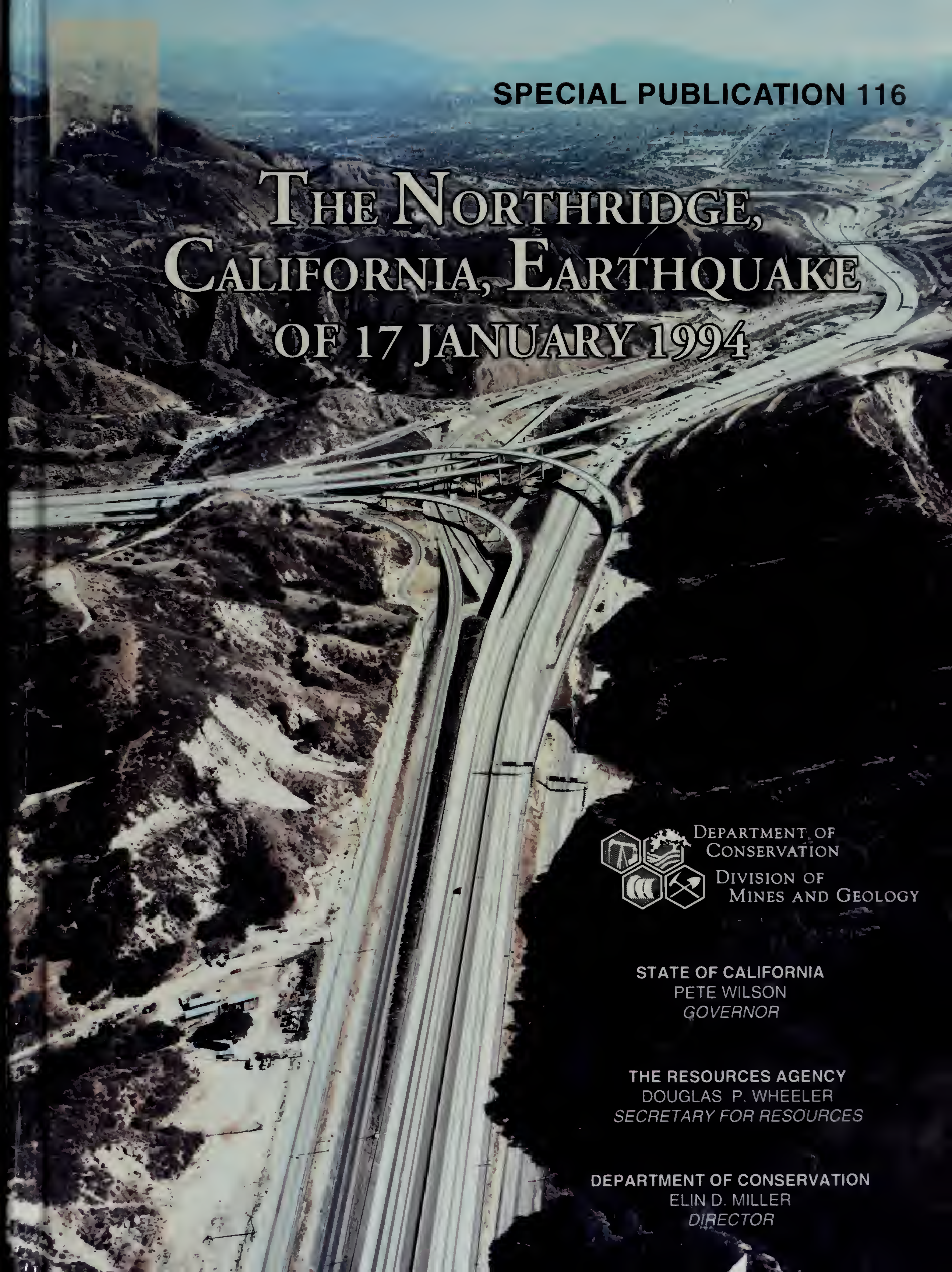


SPECIAL PUBLICATION 116

THE NORTHRIDGE, CALIFORNIA, EARTHQUAKE OF 17 JANUARY 1994

DEPARTMENT OF CONSERVATION
DIVISION OF MINES AND GEOLOGY

STATE OF CALIFORNIA
PETE WILSON
GOVERNOR

THE RESOURCES AGENCY
DOUGLAS P. WHEELER
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
ELIN D. MILLER
DIRECTOR

SPECIAL PUBLICATION 116

The Northridge, California, Earthquake of 17 January 1994

Edited by

Mary C. Woods and W. Ray Seiple

1995

CALIFORNIA DEPARTMENT OF CONSERVATION
Division of Mines and Geology
801 K Street
Sacramento, California 95814-3531

CONTENTS

INTRODUCTION
NORTHRIDGE EARTHQUAKE, 17 JANUARY 1994

by

Mary C. Woods[1] and W. Ray Seiple[1]

The purpose of this report is to bring together in one volume the information presently known concerning geological, seismological, sociological, mitigational and recovery aspects of the M 6.7 Northridge earthquake of January 17, 1994. This earthquake on a previously unmapped fault beneath the ground surface has created a turning point in earthquake research for the geoscience community and new hazard reduction concerns for social and governmental agencies. The earthquake virtually affected three county areas: Los Angeles, Ventura, and Orange. Researchers and scientists are still analyzing data from the earthquake. Many people, agencies, and institutions continue to be occupied with the aftermath of the event.

Until 1982, the damaging earthquakes that have occurred in California have been on mapped faults. Throughout the historical record of earthquakes in California the San Andreas Fault has received the most attention – dread from the public and the focus of earth scientists. This attention was justified because this fault, which traverses almost the entire length of California, was the cause of the great Fort Tejon earthquake (M 8.3) in January 1857, and the great San Francisco earthquake (M 8) in April 1906.

For the past decade the activity on unmapped subsurface faults, called blind thrust faults, has claimed more and more attention. Blind thrust faults are not completely understood, but are thought to be related to tectonic motion along the plate boundary generally demarcated by the surface expression of the San Andreas Fault in the area known as the "big bend." The current rate of seismicity in the Los Angeles basin seems to indicate that there will be an active trend for the next decade in connection with release of tectonic strain built up in the western portion of the Transverse Ranges.

Four recent earthquakes on blind thrust faults occurred prior to the latest of the earthquakes caused by a previously unmapped blind thrust fault. The 1994 Northridge earthquake (M 6.7) struck the densely populated Northridge area at 4:30 am (PST) on Monday, January 17, 1994, and drastically disrupted the lives of thousands of people. Structural damage in this portion of the San Fernando Valley in the northern part of the Los Angeles basin was severe and affected over 14,000 buildings in the area. Strong horizontal and vertical ground motion lasting up to 10 seconds caused the collapse of unreinforced masonry and tilt-up buildings, and parking structures of precast construction, widespread damage to welded steel moment frame buildings, and to homes, especially wood frame structures.

Damage occurred in the counties of Los Angeles, Ventura, and Orange and at relatively distant locations from the epicenter 14 km below Northridge, affecting concrete bridges and freeway structures, some coastal cities, and the Port of Los Angeles. There were 57 deaths, over 9,000 people were injured, and thousands in the Northridge vicinity were left without utilities and many homes were damaged to the extent that they were uninhabitable. The damage cost estimate reached $20 billion.

The Northridge earthquake has impressed the scientific community with the need to study and identify the blind thrust fault systems underlying the metropolitan Los Angeles area. This earthquake and the other recent events of 1982, 1983, 1985, and 1987 that have occurred on blind thrust faults remind the public that constant preparedness is advisable and alert scientists to the fact that there is still more to learn about the ever changing dynamics of our State. A new chapter in earthquake science has been opened as well as a redirection of programs by lead government agencies in mitigation, hazard reduction, and recovery efforts.

The papers assembled in this publication reflect the most definitive information on the Northridge earthquake available at the time of publication. The volume will be a useful resource and reference for the public, consultants, and researchers involved in various topics related to earthquake hazards, mitigation, and recovery. The Department of Conservation, Division of Mines and Geology dedicates this volume to the many scientists and organizations who have generously contributed papers and gratefully acknowledges the effort of every contributor to further the economic, social, and scientific understanding of the event for the benefit of the citizens of California.

The editors thank Ross Martin, Division of Mines and Geology graphic artist, for his effective graphics and format design for this volume.

[1]California Department of Conservation, Division of Mines and Geology, Sacramento, California

LIST OF CONTRIBUTORS

The following alphabetical listing presents the author/contributors and their professional affiliations.

Adams, Justin L.
Governor's Office of Planning and Research
Sacramento, California

Andrews, Richard
Governor's Office of Emergency Services
Sacramento, California

Augello, Anthony J.
Department of Civil Engineering
University of California
Berkeley, California

Barrows, Allan G.
California Department of Conservation
Division of Mines and Geology
Los Angeles, California

Bellet, Dennis
California Department of General Services
Division of the State Architect
Sacramento, California

Bender, Sylvia
California Department of Conservation,
Division of Mines and Geology, Library
Sacramento, California

Bray, Jonathan D.
Department of Engineering
University of California, Berkeley, California

Bryant, William A.
California Department of Conservation
Division of Mines and Geology
Sacramento, California

Chittenden, Robert
California Department of General Services
Division of State Architect,
Sacramento, California

Cinti, Francesca R.
Instituto National di Geofisica
Roma, Italy

Darragh, Robert
California Department of Conservation,
Division of Mines and Geology
Strong Motion Instrumentation Program
Sacramento, California

Dengler, Lori
Humboldt Earthquake Education Center
Humboldt State University
Arcata, California

Dewey, James W.
United States Geological Survey
Denver, Colorado

Durkin, Michael E.
Durkin and Associates
Woodland Hills, California

Fumal, Thomas E.
United States Geological Survey
Menlo Park, California

Garvin, Cristofer D.
United States Geological Survey
Menlo Park, California

Greenwood, Richard B.
California Department of Conservation
Division of Mines and Geology
Los Angeles, California

Hamilton, John C.
United States Geological Survey
Menlo Park, California

Hart, Earl W.
California Department of Conservation
Division of Mines and Geology
San Francisco, California

Hauksson, Egill
Seismological Labratory
Div. of Geological and Planetary Sciences
California Institute of Technology
Pasadena, California

Hebein, Jeffrey J.
California Department of Conservation
Div. of Oil, Gas, and Geothermal Resources
Long Beach, California

Hecker, Suzanne
United States Geological Survey
Menlo Park, California

Huang, Moh
California Department of Conservation
Division of Mines and Geology
Strong Motion and Instrumentation Program
Sacramento, California

Irvine, Pamela J.
California Department of Conservation
Division of Mines and Geology
Los Angeles, Californa

Kavazanjian, Edward Jr.
GeoSyntec Consultants
Huntington Beach, California

Matasović, Neven
GeoSyntec Consultants
Huntington Beach, California

McCrink, Timothy P.
Department of Conservation
Division of Mines and Geology
Sacramento, California

Moley, Kathy
Humboldt Earthquake Education Center
Humboldt State University
Arcata, California

Mujumdar, Vilas
California Department of General Services
Division of the State Architect
Sacramento, California

Mulqueen, Stephen P.
California Department of Conservation
Div. of Oil, Gas, and Geothermal Resources
Ventura, California.

Pandya, Sharad
Office of Statewide Health Planning
and Development
Sacramento, California

Petersen, Mark D.
California Department of Conservation
Division of Mines and Geology
Sacramento, California

Ponti, Daniel J.
United States Geological Survey
Menlo Park, California

Powers, Thomas J.
United States Geological Survey
Menlo Park, California

Ranous, Richard
Governor's Office of Emergency Services
Earthquake Preparedness Project
Pasadena, California

Reagor, B.G.
United States Geological Survey
Denver, Colorado

Real, Charles R.
California Department of Conservation
Division of Mines and Geology
Sacramento, California

Romero, Philip J.
Governors' Office
Sacramento, California

Rymer, Michael J.
United States Geological Survey
Menlo Park, California

Sanchez, Richard
California Department of Water Resources
Division of Safety of Dams
Sacramento, California

Savage, William U.
Pacific Gas and Electric Company
San Francisco, California

Schwartz, David P.
United States Geological Survey
Meno Park, California

Seed, Raymond B.
Department of Civil Engineering
University of California
Berkeley, California

Shakal, Anthony
California Department of Conservation
Division of Mines and Geology
Strong Motion Instrumentation Program
Sacramento, California

Tan, Siang S.
California Department of Conservation
Division of Mines and Geology
Los Angeles, California

Tierney, Kathleen
Disaster Research Center
University of Delaware
Newark, Delaware

Toppozada, Tousson R.
California Department of Conservation
Division of Mines and Geology
Sacramento, California

Treiman, Jerome A.
California Department of Conservation
Division of Mines and Geology
Los Angeles, California

Yashinsky, Mark
California Department of Transportation
Office of Earthquake Engineering
Sacramento, California

SECTION I

The Earthquake

Greenwood, R.B., 1995, Regional geologic overview of the Los Angeles basin *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 1-8.

REGIONAL GEOLOGIC OVERVIEW OF THE LOS ANGELES BASIN

by

Richard B. Greenwood[1]

INTRODUCTION

This paper considers the seismicity and tectonic setting of the January 17, 1994 Northridge earthquake in the densely urbanized San Fernando, Santa Clarita and Simi Valleys and adjacent east-west trending ranges of the Santa Susana Mountains, Simi Hills, and the Santa Monica Mountains (Figure 1). These three synclinal valleys are filled with unconsolidated Holocene sediments and older sedimentary rocks. The three adjacent anticlinally folded ranges, each at least partially bounded by thrust fault boundaries, are typical features of the central Transverse Ranges of southern California.

This paper also considers the seismicity of the western part of the Los Angeles basin, between the Palos Verdes Peninsula and the Santa Monica Mountains. The Los Angeles basin is dominated by northwest-trending right lateral faults, including the Newport-Inglewood and the Palos Verdes fault zones, and adjacent anticlinal uplifts. The intervening deep synclinal troughs are filled with poorly-consolidated Upper Pleistocene and unconsolidated Holocene sediments.

PLATE TECTONICS AND RELATED CRUSTAL DEFORMATION

Numerous authors have presented historical geologic summaries, regional strain syntheses, and resulting deformational scenarios from the perspective of plate tectonic models (Humphreys and Weldon, 1994; Atwater, 1989; Yerkes, 1985; Dickinson, 1981). The current driving force of local deformation is the interaction between the East Pacific plate and the North American plate along a transform boundary. This current plate configuration contrasts with regional tectonics prior to 29 million years ago (ma), when fore-arc sedimentation was controlled by subduction beneath the North American plate. Contact between the subduction zone and the East Pacific Rise (about 29 ma) led to the development of transform faulting west of the present San Andreas Fault Zone (Dickinson and Snyder, 1979). A progressive westward decrease in slip rates across this transform system was noted by Bird and Rosenstock (1984), with slip rates updated through compilation by Petersen and Wesnousky (1994): from the southern San Andreas Fault (25-42 mm/yr) to the San Jacinto Fault (8-18 mm/yr); Whittier-Elsinore Fault zone (2.5-5 mm/yr) to the Newport-Inglewood Fault zone (0.4-1.0 mm/yr). Wright (1991) suggests that the decreasing slip rates may imply an increase in shear in the Pacific plate with proximity to the North American plate, which can be interpreted to suggest a broad zone of viscous drag within the mantle.

North-south convergence, which is so prevalent in the Transverse Ranges, is driven by movement along this plate margin system of strike-slip faults. Relative right lateral motion between the North American and the Pacific plates is at least 56 mm/year, if averaged over the last 5 ma (Moore, 1981). This slip rate includes 33 mm/year along the San Andreas Fault Zone north of the Transverse Ranges (Thatcher, 1979), and 23 mm/year attributed to other faults in the San Andreas system plus faulting and folding in the Transverse Ranges (Yerkes, 1985). The deformational features which have resulted from north-south compression include mountain building along convergent faults, basin development, regional warping and uplift—indicated by deformation of late Quaternary marine and nonmarine terrace deposits, and earthquakes (Yerkes, 1985). Deformation in the Los Angeles basin has generally been recognized as strike slip faulting on northwest-trending right lateral faults with associated wrench fault uplifts (Wilcox and others, 1973). More recent interpretations recognize the importance of deformation attributable to active convergence including exposed and blind thrust faults (Hauksson and Jones, 1989; Davis, Namson, and Yerkes, 1989; Shaw and Suppe, 1993).

Previous Fault Activity in the Los Angeles Basin

As cited above, the dominant types of faulting in the Los Angeles region are right lateral faults of the San Andreas Fault system, which include the subparallel Newport-Inglewood, Whittier-Elsinore, and the San

[1]California Department of Conservation, Division of Mines and Geology, Southern California Regional Office, Los Angeles, California

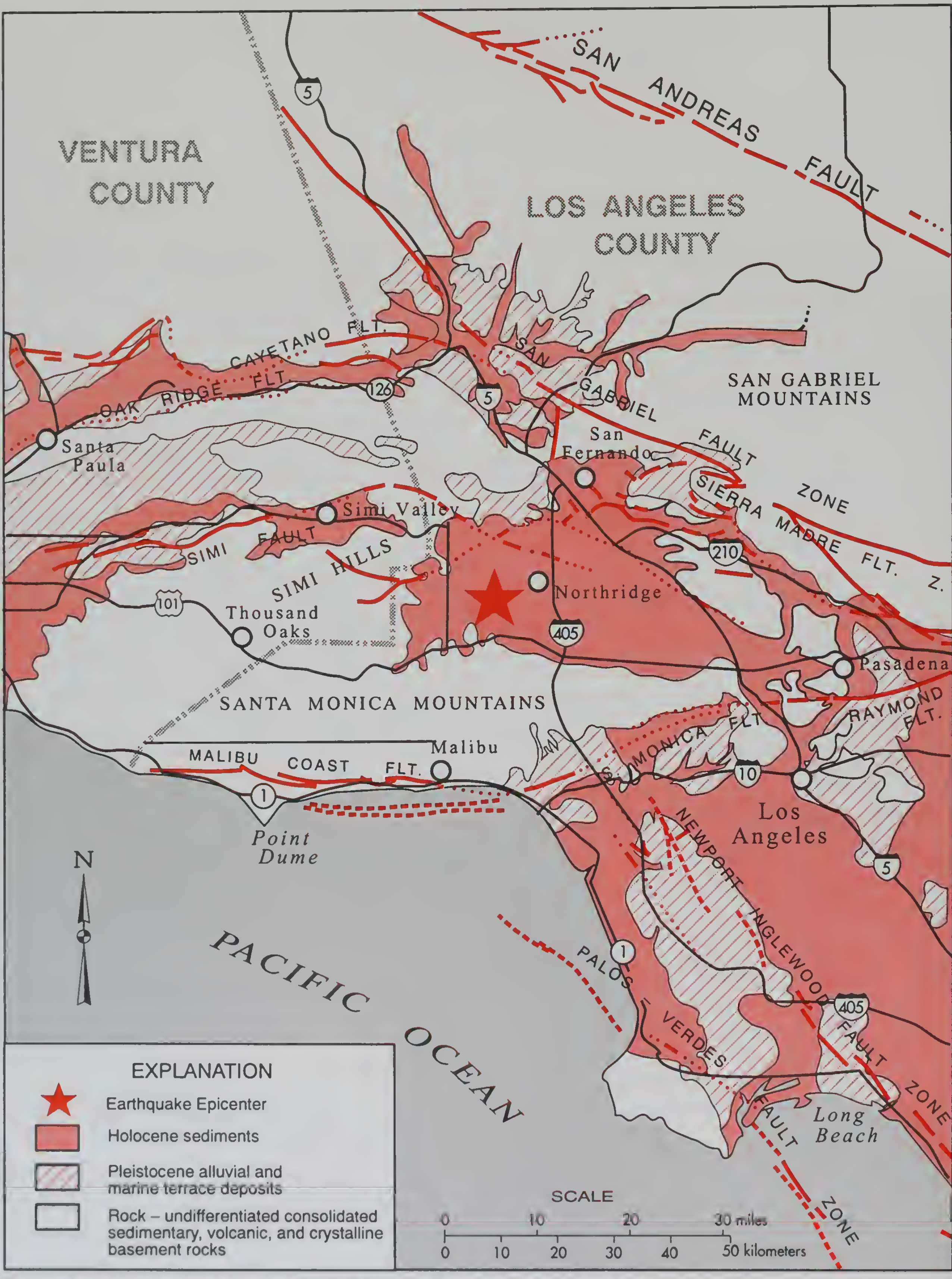


Figure 1. Generalized geology of the Los Angeles area. From Stewart, 1994, with faults from Jennings (1994).

Jacinto fault zones, and blind thrust faults, so-called because they lack surface fault rupture. The strong correlation between the known and inferred locations of earthquakes from 1800 to 1978 and the locations of faults with surface expression has been cited by Yerkes (1985) as a strong indicator of potential locations for future damaging earthquakes. From this perspective, which predates the Landers and Northridge events, faults identified as major southern California sources of historical damaging earthquakes include: the San Andreas, Newport-Inglewood, and San Jacinto fault zones, and the Raymond Fault, the San Fernando Fault, and the Santa Barbara channel faults. Yerkes also suggests that the absence of historical seismic activity on the San Cayetano, Sierra Madre and Cucamonga faults is likely more indicative of a longer recurrence interval, rather than lower seismic hazard.

The Division of Mines and Geology geologists in the Alquist-Priolo Program, recognizing the likely association between demonstrable Holocene fault rupture and the potential for future fault rupture, also recognized the importance of the Verdugo and Whittier-Elsinore fault zones (Hart, 1994). Active faults outside the purview of the Alquist-Priolo Program include offshore faults and blind thrust faults. Local offshore faults of Holocene age include the Ventura Fault, offshore Malibu Coast Fault, Redondo Canyon Fault, and the offshore Cabrillo and Palos Verdes-Coronado Bank fault zones (Jennings, 1992).

GEOLOGIC AND STRUCTURAL HISTORY OF THE LOS ANGELES BASIN

Numerous models have been presented to explain the structural evolution of the Los Angeles basin. One of the primary challenges in explaining the development of the Los Angeles basin is the recognition of a structural mechanism that results in a rapidly deepening basin which permitted the massive accumulation of sediments in a relatively short period of time. Mechanisms summarized by Biddle (1991) include: (1) uplift and subsidence (Driver, 1948), (2) horst and grabben extension tectonics, based on comparisons between sediment-starved basins in the continental borderlands and the basins and ranges of Nevada (Barbat, 1958), (3) rifting associated with sea floor spreading and rafting on detachment surfaces (Yeats, 1968), (4) pull-apart basins along strike slip faults (Crowell, 1974a, 1974b, 1976), (5) basins formed by rotational tectonics, supported by paleomagnetic data (Luyendyk and Hornafius, 1987), and (6) Miocene extension tectonics along crustal detachment surfaces (Wright, 1991 and Crouch and Suppe, 1993). Stratigraphic constraints to modeling are summarized by Yerkes and others (1965) and indicate that sedimentation in the Los Angeles basin began in late Oligocene through the middle Miocene and was fully developed during the late Miocene and Pliocene. Basin development was curtailed by post mid-Pleistocene Pasadenan deformation.

Developmental histories of the Los Angeles basin presented by numerous authors were synthesized, and graphically summarized (Figure 2) by Wright (1991). Fore-arc deposition prevailed prior to deposition of the Sespe Formation. The Sespe Formation (37 to 22 ma) reflects a period of crustal uplift associated with the Pacific-Farallon spreading ridge approaching the North American plate. The earliest stages of possible rifting and crustal extension accompanied the deposition of the lower Miocene Vaqueros Formation (29? to 22 ma). From 22 ma to 16 ma, high heat flow promoted the development of local basins, while the greater basin remained undisturbed (evidenced by interbedded marine and nonmarine deposition in the Santa Monica Mountains, Puente Hills, and the Santa Monica Mountains). Local volcanism occurred 16 ma to 13 ma along the Malibu Coast-Santa Monica-Hollywood-Raymond structural boundary between the Transverse Ranges and the Los Angeles basin. From 12 ma to 9 ma regional and uniform subsidence resulted in widespread deposition of deepwater sediments with abundant organic material. Two extensive submarine fans, the Tarzana fan and the Puente fan, formed and deposited deepwater sands from 9 ma to 6.5 ma.

The extensional phase of basin development occurred 7 ma to 3 ma during latest Miocene and early Pliocene extension (Wright, 1991). Extension was likely concurrent with the 4.9 ma to 3.2 ma opening of the Gulf of California and the eastward shift of the San Andreas Fault Zone. This extension was locally expressed as vertical movement along the Santa Monica, Las Cienegas, and Whittier faults and uplift of the Palos Verdes hills area, and subsidence of the central Los Angeles basin trough and Fullerton embayment. The Santa Clara trough, north of the San Fernando Valley, was also thought to have opened towards the greater Ventura basin during early Pliocene time. Convergent deformation (Pasadenan) began 3.5 ma, accelerated in the mid-Pleistocene, and continues today. Current deformation involves southward directed crustal shortening, uplift of the Transverse Ranges, propagation of blind thrusts, and basin-filling with clastic sediments (Wright, 1991).

BLIND THRUST FAULTS

The deep, gentle to moderate-dipping, compression fault focal mechanisms revealed by the Coalinga earthquake, Whittier Narrows earthquake, and the recent Northridge earthquake, have highlighted the seismogenic significance of blind thrust faults in regional geologic reconstructions. Retrodeformable reconstructions readily accommodate the geometric constraints and kinematic

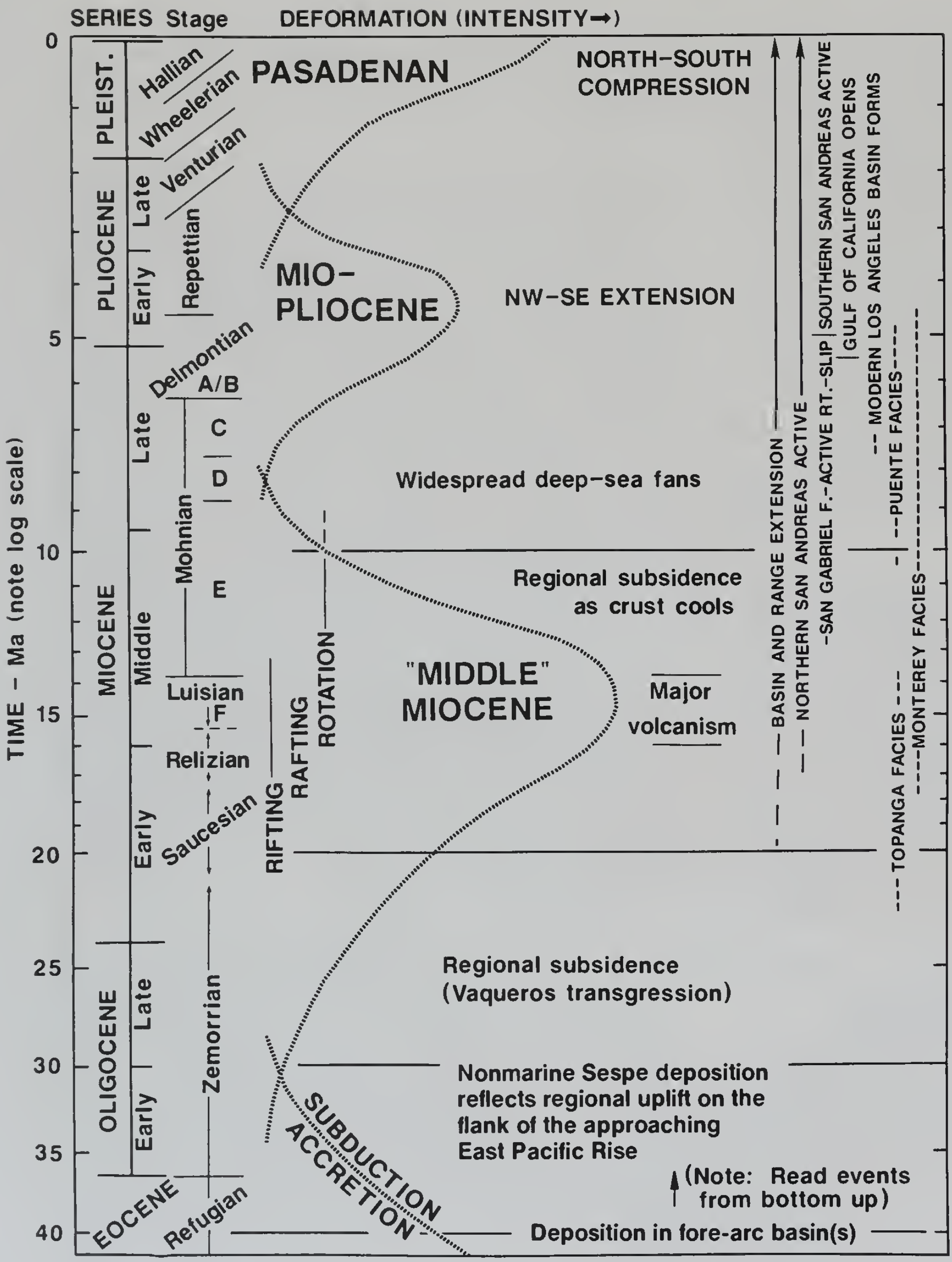


Figure 2. Chronology of major Cenozoic events in the Los Angeles region. Curve shows intensity of tectonic deformation. Local biostratigraphic zonation and major depositional facies are also shown. Boundaries between late Neogene stages are shown as slanting lines to represent the time-transgressive nature of these provincial units. Used by permission; Wright, 1991.

contributions to regional reconstructions, which blind thrust faults present. Such cross-sections are constrained by an accounting of mass balance and cumulative slip on regional and local faults, resulting in possible but not unique interpretations (Davis, Namson, and Yerkes, 1989).

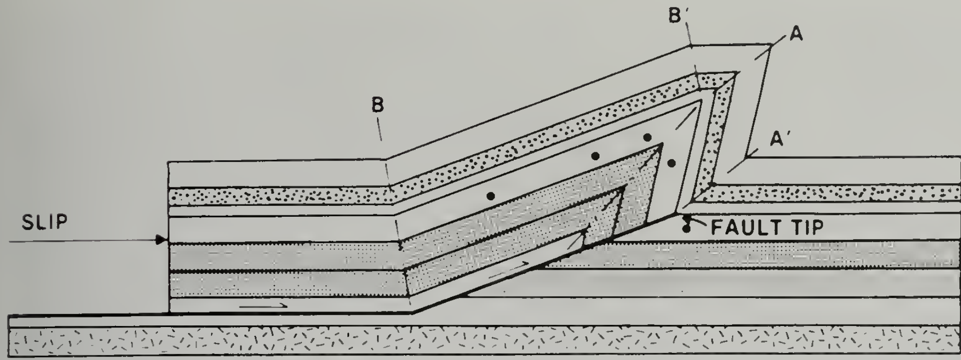
Blind thrust faults are concealed, low to moderate-angle fault surfaces which may be structurally linked to low angle detachments or decollements. They may be accompanied by overlying coseismic fault-propogation folds or fault-bend folds, as illustrated in Figure 3. Fault-bend folds, as applied to the Los Angeles basin by Suppe and others (1992), requires the existence of two fault surfaces that are joined by a thrust ramp surface. As slip is translated through the junction of a blind thust surface and inclined thrust ramp, conservation of area in deformation requires fold formation that reflects the size and shape of underlying blind thrusts.

Blind Thrust Faults in Central California

Previous earthquakes generated from blind thrust faults in central California include the New Idria, Coalinga, and Kettleman Hills earthquakes which occurred during a 32 month period on adjacent offset ramp segments of the same blind thrust structure (Stein and Ekstrom, 1992; Namson and Davis, 1988). The New Idria earthquake (M_L=5.4) occurred on October 25, 1982, located about 20 km northwest of Coalinga, at a depth of 11 km (Stover, 1985). The Coalinga earthquake (M_L=6.5) occurred on May 2, 1983, near the town of Coalinga, at a depth of 10 km. This earthquake caused an estimated $10 million damage and caused 0.5 m uplift on nearby Anticline Ridge (Stover and Coffman, 1993). The Kettleman Hills earthquake (M_L=5.8) occurred on August 4, 1985, near the town of Avenal, at a depth of 11 km (Stover and Coffman, 1993).

Blind Thrust Faults in the Southwestern and Central Los Angeles Basin

The Whittier Narrows earthquake (M_L=5.9) focused attention on blind thrust faults in the Los Angeles basin. It occurred in the east Los Angeles region, on October 1, 1987, and caused approximately $358 million damage (Stover and Coffman, 1993). The spatial distribution of the mainshock and aftershocks, and the focal mechanisms of the mainshock indicated that the causative fault was a west-striking thrust fault that dips 25° north, with no recorded surface rupture (Hauksson and others, 1989). This basement-rooted structure occurred at a depth of 14.6 km ±0.5 km, and is contained within the Elysian Park fault system—a postulated 10-15 km wide blind



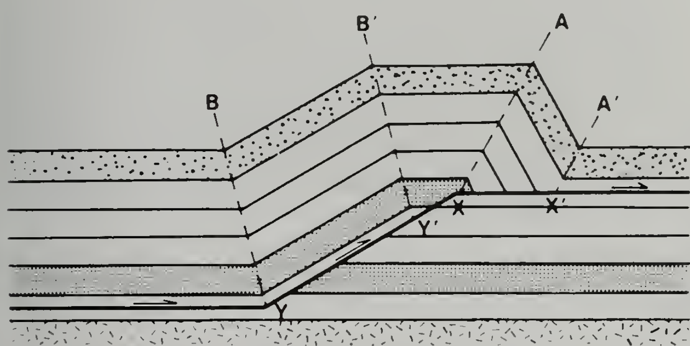


Figure 3. Upper figure: Anticline caused by fault-propagation folding. The bedding-plane thrust cuts cross section, and a fold forms with the synclinal axis terminating at the propagating fault tip. Fault slip progressively decreases to zero at the tip of the propagating fault. Lower figure: Anticline caused by fault-bend folding as a thrust sheet is translated over a nonplanar fault. The front limb (A-A') forms as the hanging-wall cutoff (X'-Y') is translated from the ramp (X-Y) onto the upper bedding-plane thrust. The back limb (B-B') forms as the hanging wall is translated up the ramp. From Namson and Davis(1988), after Suppe and Namson (1979); used by permission.

thrust transition zone between the west-striking convergent faults of the Transverse Ranges to the north and the northwest-striking strike slip faults of the Peninsular Ranges to the south (Hauksson and Jones, 1989). Coseismic deformation occurred as domal uplift, with a peak uplift of 50 mm, over a region of 5-8 km (Lin and Stein, 1989).

Retrodeformable cross sections generated by Davis, Namson, and Yerkes (1989) presented geometrically and kinematically viable reconstructions of the Los Angeles basin which modeled blind thrusts beneath the Santa Monica Mountains anticlinorium (Elysian Park fault), Palos Verdes anticlinorium and the adjacent Torrance-Wilmington fold and thrust belt. These regional reconstructions also link surface thrusts under the Verdugo and San Rafael Hills and San Gabriel Mountains to underlying detachment surfaces. The study of focal mechanisms of small to moderate-sized earthquakes (M=2.5-5.9) by Hauksson (1990), provided further definition of the Elysian Park and the Torrance-Wilmington fold and thrust belts as both being attributable to movement on blind thrust faults. The Torrance-Wilmington structural zone was previously associated with wrench faulting along major strike slip faults by Wilcox and others, (1973). Hauksson (1990) further subdivided the Elysian Park fold and thrust belt into five segments and divided the Torrance-Wilmington fold and thrust belt into three segments (Figure 4) from the basis of 1977 to 1989 seismicity and geologic data.

Western Los Angeles basin structural modeling was further refined through definition of the Compton-Los Alamitos blind thrust ramp by Shaw and Suppe (1993), from the basis of upward-narrowing kink-bands, imaged in seismic reflection profiles. These profiles were interpreted using high resolution seismic profiles, well logs, regional seismicity, surface geology, and fault-bend fold modeling (Suppe, 1983). Models were then compared with gravity anomalies modeled by Henderson (1993). The modeled Compton blind thrust ramp dips 23° northeast from a depth of 17 km or less to a depth of 5 km. Offsets in the overlying Compton-Los Alamitos fold suggest three segments of the Compton blind thrust ramp (Figure 5). Comparison between folds in the Compton-Los Alamitos and southern Elysian Park trends suggest that underlying blind faults may be linked across the Los Angeles basin by near-horizontal detachment surface (Shaw and Suppe, in press).

Blind Thrust Faults in the Northwestern Los Angeles Basin and Environs

The Northridge earthquake (M_w=6.7) occurred on January 17, 1994, at 12 30 (UTC). It was located approximately 2 km southwest of Northridge, at a focal depth of 19 km, on a south-dipping blind thrust fault (Hauksson and others, 1994). Displacement averaged 1.5 m with a maximum displacement of 3.5 m on a plane that strikes 332°, dips 42° S, with a slip vector azimuth of 109° (Wald and Heaton, 1994). Most slip occurred between 6 km to 13 km, with no slip occurring above 5 km (Hudnut, and others, 1994). As modeled by Davis and Namson (1994) using balanced cross-sections, surface geology, and oil company data, the causative blind thrust fault is a mid-crustal thrust ramp under the San Fernando Valley that is related to the development of the Santa Susana Mountains anticlinorium.

Yeats and Huftile (1995) note that Northridge earthquake aftershock focal mechanisms indicate a structure that has a moderate dip down

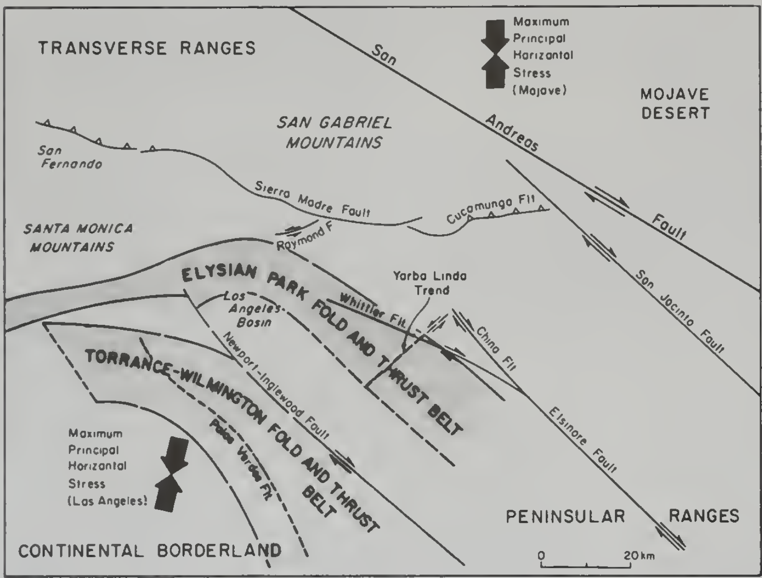
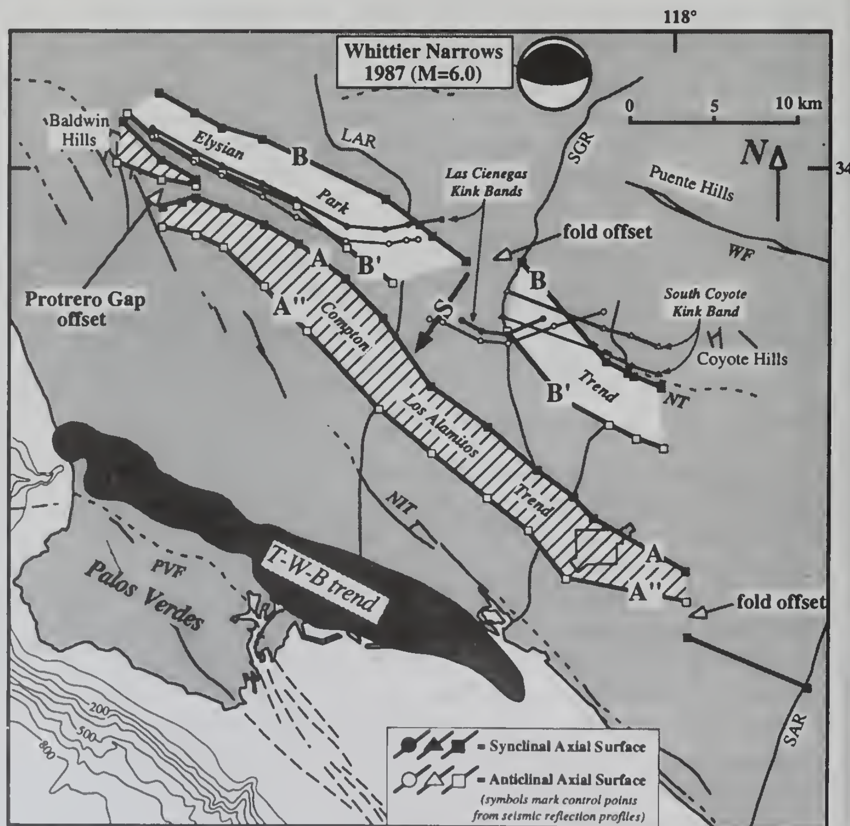


Figure 4. Schematic tectonic map of the Los Angeles basin showing mappable surficial late Quaternary faults and the Yorba Linda seismicity trend. The Elysian Park and Torrance-Wilmington fold and thrust belts are shown as shaded areas. Maximum compression horizontal principal stresses for the Mojave segment of the San Andreas Fault are also shown with thick arrows. White lines delineate proposed fault segmentation. From Hauksson, 1990.

to 18 km, which shows no indication of flattening. This structure is interpreted to be an eastward continuation of the Oak Ridge Fault, from the adjacent Ventura basin. West of the Ventura basin in the Santa Barbara Channel, the offshore Oak Ridge trend and adjacent trends have recently been modeled, using fault-bend fold interpretations and high resolution seismic data, to define the Channel Islands blind thrust ramp (Shaw and Suppe, 1994). This thrust ramp has been associated with a swarm of more than 400 earthquakes (M=0.5-4.0) that occurred under the offshore Oak Ridge trend in April, 1984. Focal mechanisms have nodal planes that are horizontal or dip 20° N (Henyey and Teng, 1985). The modeled Channel Islands Fault ramps upward from at least 16.5 km beneath the offshore Oak Ridge structural trend, with related active faults modeled between 2-5 km beneath the Blue Bottle structural trend.

Figure 5. A parallel projection axial surface map of active fold trends around the central Los Angeles basin. The Compton-Los Alamitos kink-band (A-A") overlies the Compton blind-thrust ramp, which dips to the northeast. The south flank of the Elysian Park trend consists of two levels of faulting and folding: a deep kink-band (B-B') above a decollement in the central basin that is joined to the northeast by the Elysian Park thrust ramp, and shallow kink bands above the Las Cienegas and Coyote blind thrusts. Kink-band widths A-A" and B-B' approximate dip-slip magnitudes on the underlying fault segments. Offsets of the fold trends overlie fault discontinuities that define segmentation of the underlying fault ramps, which may affect rupture areas. S = inferred slip direction; LAR = Los Angeles River; SGR = San Gabriel River; SAR = Santa Ana River. Reprinted with permission; Shaw and Suppe, 1993; Shaw and Suppe, in press.



DISCUSSION

The growing recognition of blind thrust faults as a significant source of seismic activity has also fostered a reconsideration of regional geologic models which were previously based solely on strike slip and thrust fault mechanisms. Hauksson and Jones (1989) postulated the presence of a 10 to 15 km-wide transition zone of seismogenic blind thrusts, which they named the Elysian Park Fault system. This provides a structural transition between the west-trending thrust fault and fold-dominated Transverse Ranges to the north and the northwest-trending right lateral fault-dominated Peninsular Ranges to the south. The coexistence of large strike slip faults and thrusting suggests that the thrust and strike slip movements occur above a decoupling or detachment surface (Hauksson, 1990). Shaw and Suppe (in press) have also suggested that the Elysian Park and Compton blind thrust complexes may be structurally linked by a near-horizontal thrust system beneath the Los Angeles basin. The required pre-existence of detachment surfaces for the formation of blind thrust development further recognizes extensional models for the Los Angeles basin (Wright, 1991), and for the Continental Borderlands (Crouch and Suppe, 1993). The recent Northridge earthquake, with its pending regional interpretations (Davis and Namson, 1994) and (Yeats and Huftile, 1995) has further focused attention on the importance of accurately characterizing and modeling blind thrust fault ramps as an important seismogenic source.

ACKNOWLEDGMENTS

Review comments were gratefully received from Thom Davis (Davis and Namson, Valencia, California), Roy Kroll (Zeiser Geotechnical, Costa Mesa, California), John Shaw (Texaco Exploration Research, Houston, Texas) and by Russ Miller and Mark Peterson, California Division of Mines and Geology.

REFERENCES

Atwater, T.M., 1989, Plate tectonic history of the northeast Pacific and western North America *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Eastern Pacific Ocean and Hawaii: Geological Society of America, The Geology of North America, v. N, p. 21-72.

Barbat, W.F., 1958, The Los Angeles basin area, California *in* Weeks, L.G., ed., Habitat of Oil: American Association of Petroleum Geologists, p. 62-77.

Biddle, K.T., 1991, The Los Angeles basin, an overview *in* Active Basin Margins: American Association of Petroleum Geologists Memoir 52, p. 5-24.

Bird, P., and Rosenstock, R.W., 1984, Kinematics of present crust and mantle flow in southern California: Geological Society of America Bulletin, v. 95, p. 946-957.

Crouch, J.K., and Suppe, J., 1993, Late Cenozoic tectonic evolution of the Los Angeles basin and inner California borderland – A model for core complex-like crustal extension: Geological Society of America Bulletin, v. 105, p.1415-1434.

Crowell, J.C., 1974a, Sedimentation along the San Andreas fault *in* Dott Jr., R.H., and Shaver, R.H.,eds., Modern and ancient geosynclinal sedimentation: SEPM Special Publication 19, p. 292-303.

Crowell, J.C., 1974b, Origin of late Cenozoic basins in southern California *in* Dickinson, W.R., ed., Tectonics and Sedimentation: SEPM Special Publication 22, p. 190-204.

Crowell, J.C., 1976, Implications for crustal stretching and shortening of coastal Ventura basin, California *in* Howell, D.G., ed., Aspects of the Geologic History of the California Continental Borderland: Pacific Section, American Association of Petroleum Geologists Miscellaneous Publication 24, p. 365-382.

Davis, T.L., and Namson, J., 1994, A balanced cross section of the 1994 Northridge earthquake, southern California: Nature, v. 372, no. 6502, p. 167-169.

Davis, T.L., Namson, J.S., and Yerkes, R.F., 1989, A cross section of the Los Angeles area - Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard: Journal of Geophysical Research, v. 94, no. B7, p. 9644-9664.

Dickinson, W. R., 1981, Plate tectonics and the continental margin of California *in* Ernst, W.G., ed., The Geotectonic Development of California (Rubey Volume 1): Prentice-Hall, Englewood Cliffs, N.J., p. 1-28.

Dickinson, W.R., and Snyder, W.S., 1979, Geometry of triple junctions related to San Andreas transform: Journal of Geophysical Research, v. 84, no. 2, p. 561-572.

Driver, H.L., 1948, Genesis and evolution of the Los Angeles basin, California: American Association of Petroleum Geologists Bulletin, v. 32, p. 109-125.

Hart, E.W., 1994, Fault rupture hazard zones in California: Division of Mines and Geology Special Publication 42, p. 34.

Hauksson, E., 1990, Earthquakes, faulting, and stress in the Los Angeles basin: Journal of Geophysical Research, v. 95, B10, p. 15,365-15,394.

Hauksson, E., Hutton, K., Kanamori, H., Jones, L., Mori, J., 1994, The M_w 6.7 Northridge, California earthquake of January 17, 1994 and its aftershocks: Seismological Society of America (abstracts), 89th Annual Meeting, April, 1994.

Hauksson, E., and Jones, L.M., 1989, The 1987 Whittier Narrows earthquake sequence in Los Angeles, southern California – Seismological and Tectonic Analysis: Journal of Geophysical Research, v. 94, No. B7, p. 9569-9589.

Henderson, M.T.,1993, A gravity and structural interpretation of the Los Angeles basin, California: Princeton University senior thesis.

Henyey, T.L., and Teng, T., 1985, Seismic studies of the Dos Cuadras and Beta Offshore Oil Fields, southern California outer continental shelf: United States Mineral Management Service final technical report.

Hudnut, K.W., Murray, M.H., Donnellan, A., Bock,Y., Fang, P., Cline,M., Feng, Y., Shen, Z., Haher, B., Herring, T., and King, R., 1994, Coseismic displacements of the 1994, Northridge, California earthquake: Seismological Society of America (abstract), Program for Northridge abstracts, Pasadena, California.

Humphreys, E.D., and Weldon, R.J., II, 1994, Deformation across the western United States – A local estimate of Pacific-North America transform deformation: Journal of Geophysical Research, v. 99, no. B10, p. 19,975-20,010.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map Number 6, scale 1:750,000.

Lin, J., and Stein, R.S., 1989, Coseismic folding, earthquake recurrence, and the 1987 source mechanism at Whittier Narrows, Los Angeles basin, California: Journal of Geophysical Research, v. 94, no. B7, p. 9614-9632.

Luyendyk, B.P., and Hornafius, J.S., 1987, Neogene crustal rotations, fault slip, and basin development in southern California *in* Ingersoll, R.V., and Ernst, W.G., eds., Cenozoic basin development of coastal California, (Rubey Volume VI): Prentice-Hall, Inc., Englewood Cliffs, New Jersey, p. 259-283.

Moore, G.W., 1981, Plate perimeters and motion vectors *in* Drummond, K.J., chairman, Plate-tectonic Map of the Circum-Pacific Region: American Association of Petroleum Geologists, scale 1:10,000,000.

Namson, J.S., and Davis, T.L., 1988, Seismically active fold and thrust belt in the San Joaquin Valley, central California: Geological Society of America Bulletin, v. 100, p. 257-273.

Petersen, M.D., and Wesnousky, S.G., 1994, Fault slip rates and earthquake histories for active faults in southern California: Bulletin Seismological Society of America, v. 84, No. 5, p. 1608-1649.

Shaw, J.H., and Suppe, J., 1993, Earthquake hazards of active blind-thrust ramps in the Los Angeles basin, California: Princeton University PhD thesis, 216 p.

Shaw, J.H., and Suppe, J., 1994, Active faulting and growth folding in the eastern Santa Barbara Channel, California: Geological Society of America Bulletin, v. 106, p.607-626.

Shaw, J.H., and Suppe, J., in press, Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California: Journal of Geophysical Research, 44 p.

Stein, R.S., and Ekstrom, G., 1992, Seismicity and geometry of a 110-km-long blind thrust fault – Synthesis of the 1982-85 California earthquake Sequence: Journal of Geophysical Research, v. 97, no. B4, p. 4865-4883.

Stewart, J.P., Bray, J.D., Seed, R.B., Siter, N., eds.,1994, Preliminary report on the principle geotechnical aspects of the January 17, 1994 Northridge earthquake: Earthquake Engineering Research Center, University of California, Berkeley, College of Engineering – Report No. UCB/EERC-94108, 245 p.

Stover, C.W., 1985, United States earthquakes, 1982: U.S. Geological Survey Bulletin 1655, 141 p.

Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568-1989 (Revised): U.S. Geological Survey Professional Paper 1527, 418 p.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684-721.

Suppe, J., Bischke, R.E., and Shaw, J.H., 1992, Regional map-view and cross-sectional determination of fault geometry and slip for blind thrusts in populated areas of southern California: Southern California Earthquake Center 1992 Report, Annual Meeting, Los Angeles, California, p.C37.

Suppe, J., and Medwedeff, D.A., 1984, Fault-propagation folding: Geological Society of America Abstracts with Programs, v. 16, p. 67.

Suppe, J., and Namson, J.S., 1979, Fault bend origin of frontal folds of the western Taiwan fold and thrust belt: Petroleum Geology Taiwan, no. 16, p. 1-18.

Thatcher, W., 1979, Systematic inversion of geodetic data in Central California: Journal of Geophysical Research, v. 84, no. 5, p.2283-2295.

Wald, D.J., and Heaton, T.H., 1994, A multidisciplinary source analysis of the 1994 (M_w 6.7) Northridge earthquake using strong ground motion, teleseismic, and geodetic data: Seismological Society of America (abstract), Program for Northridge Abstracts, Pasadena, California.

Wilcox, R.E., Harding, T.P., and Seely, D.R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74-96.

Wright, T.L., 1991, Structural geology and tectonic evolution of the Los Angeles basin, California *in* Biddle, K.T., ed., Active Margin Basins: American Association of Petroleum Geologists Memoir 52, p.35-134.

Yeats, R.S., 1968, Rifting and rafting in the southern California borderland *in* Dickinson, W.R., and Grantz, A., eds., Proceedings of Conference on Geologic Problems of San Andreas Fault System: Stanford University Publications, Stanford, California, p. 307-322.

Yeats, R.S., and Huftile, G.J., 1995, The Oak Ridge fault system and the 1994 Northridge, California earthquake: Nature, v. 373, p. 418-420..

Yerkes, R.F., 1985, Geologic and seismologic setting *in* Ziony, J.I., ed., Evaluating earthquake hazards in the Los Angeles region — An Earth Science Perspective: U.S. Geologic Survey Professional Paper 1360, p. 25-41.

Yerkes, R.F., McCulloh, T.H., Schoellhamer, J.E., and Vedder, J.G., 1965, Geology of the Los Angeles basin, California—an introduction: U.S. Geological Survey Professional Paper 420-A, 57 p.

Toppozada, Tousson, 1995, History of damaging earthquakes in Los Angeles and surrounding area *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 9-16.

HISTORY OF DAMAGING EARTHQUAKES IN LOS ANGELES AND SURROUNDING AREA

by

Tousson R. Toppozada[1]

ABSTRACT

The earthquake history within 160 km (100 mi) of downtown Los Angeles since the first reported felt event in 1769 is reviewed. The history appears to be complete at the magnitude (M) 6 or greater level for only about the last 115 years. In that short period the strongest event occurred in 1952 in Kern county (M 7.5), during an otherwise quiet interval between the 1933 Long Beach and 1971 San Fernando earthquakes. The seismicity during the 53 years preceding 1933 was mainly in the San Bernardino – San Jacinto area. The seismicity since 1971 has been mainly in the Los Angeles and Mojave Desert areas. Seismic quiescence was not observed after the great 1857 earthquake as it was for more than 50 years after the great 1906 San Francisco earthquake.

The 1971 and 1994 earthquakes that were destructive in San Fernando Valley had a smaller damaging precedent of M 5.5 to 5.9 in 1893. Only four other mainshocks of M 5.5 have occurred in Los Angeles in the last 115 years. These occurred near Long Beach in 1933, near Whittier Narrows in 1987, and north of Sierra Madre/Monrovia in 1889 and 1991.

The most destructive earthquakes in Los Angeles have been local events of M<7 occurring within 50 km of downtown. The 1857 earthquake of M 7.8 was 60 km or more from Los Angeles, and caused less damage to the low rigid adobe buildings of the time than did a local Los Angeles event of about M 6 in 1855. An 1857-type event occurring today would cause relatively more damage, particularly to the high rise buildings that would respond to long period motion.

INTRODUCTION

This review of the earthquake history of Los Angeles and surroundings discusses the length and completeness of the earthquake record, and shows when and where earthquakes have occurred and how large they were. Summary descriptions of the earthquakes and their felt and damaging effects are provided, as a guide to damaging earthquake occurrences during the short historical record in this area.The increased occurrences of damaging earthquakes in Los Angeles since 1971 are reviewed in light of the short historical record. The nature of the earthquake damage in Los Angeles is compared for local versus distant sources.

The earthquakes that have most strongly affected Los Angeles are listed in Table 1. The table lists mainshocks of M 6 within 160 km (100 mi) of downtown Los Angeles (lat. 34.0° N, long. 118.2° W), and mainshocks of $M\geq5$ within 50 km (30 mi) of Los Angeles. No aftershocks are listed.

The magnitudes and locations of the pre-1932 events are derived from intensity data (Toppozada and others, 1978, 1981; Ellsworth, 1990). The pre-1890 determinations are approximate because they are based on scant data. Moment magnitudes are listed for the events of 1857, 1933, 1971, 1973, 1981, 1987, 1992, and 1994. Local magnitudes revised by Hutton and Jones (1993) are listed for the remaining post-1932 events.

Data obtained after publication of the report by Toppozada and others (1981) has resulted in new determinations for 4 earthquakes that occurred before 1890. The 1889 epicenter was moved 0.1° northward after comparing its intensity data to the intensities of the Sierra Madre/Monrovia earthquake of 1991. The 1883 epicenter was moved from the Santa Barbara Channel northward toward the San Andreas Fault based on recently discovered information in Kern County. The location of the 1880 earthquake is determined for the first time based on recently discovered reports of damage in San Bernardino. Reports of an 1803 earthquake that damaged Mission San Gabriel are presented. Magnitudes were roughly estimated for the events of 1769, 1803, 1827, 1855, and 1858.

[1] California Department of Conservation, Division of Mines and Geology, Sacramento, California

The epicenters and magnitudes of the earthquakes listed in Table 1 are displayed on the map in Figure 1. Surface faulting is depicted only for the major 1857 and 1992 earthquakes which originated beyond the 160 km radius and propagated into it.

Organization

A list of earthquake descriptions and summarized damage effects from 1769 through 1994 is provided. This is followed by a discussion of the temporal distribution of seismicity in the Los Angeles area, including a comparison of the effects of local and distant events, and a discussion of the completeness of the earthquake record in this area. Finally, the observations from the seismicity data are summarized.

EARTHQUAKE DESCRIPTIONS

Summaries of earthquake date, location, magnitude (M) and damage effects are listed chronologically (year, month, day) for events of M≥6 within 160 km of Los Angeles, and M≥5 within 50 km of Los Angeles. The main sources of descriptions and pre-instrumental (pre-

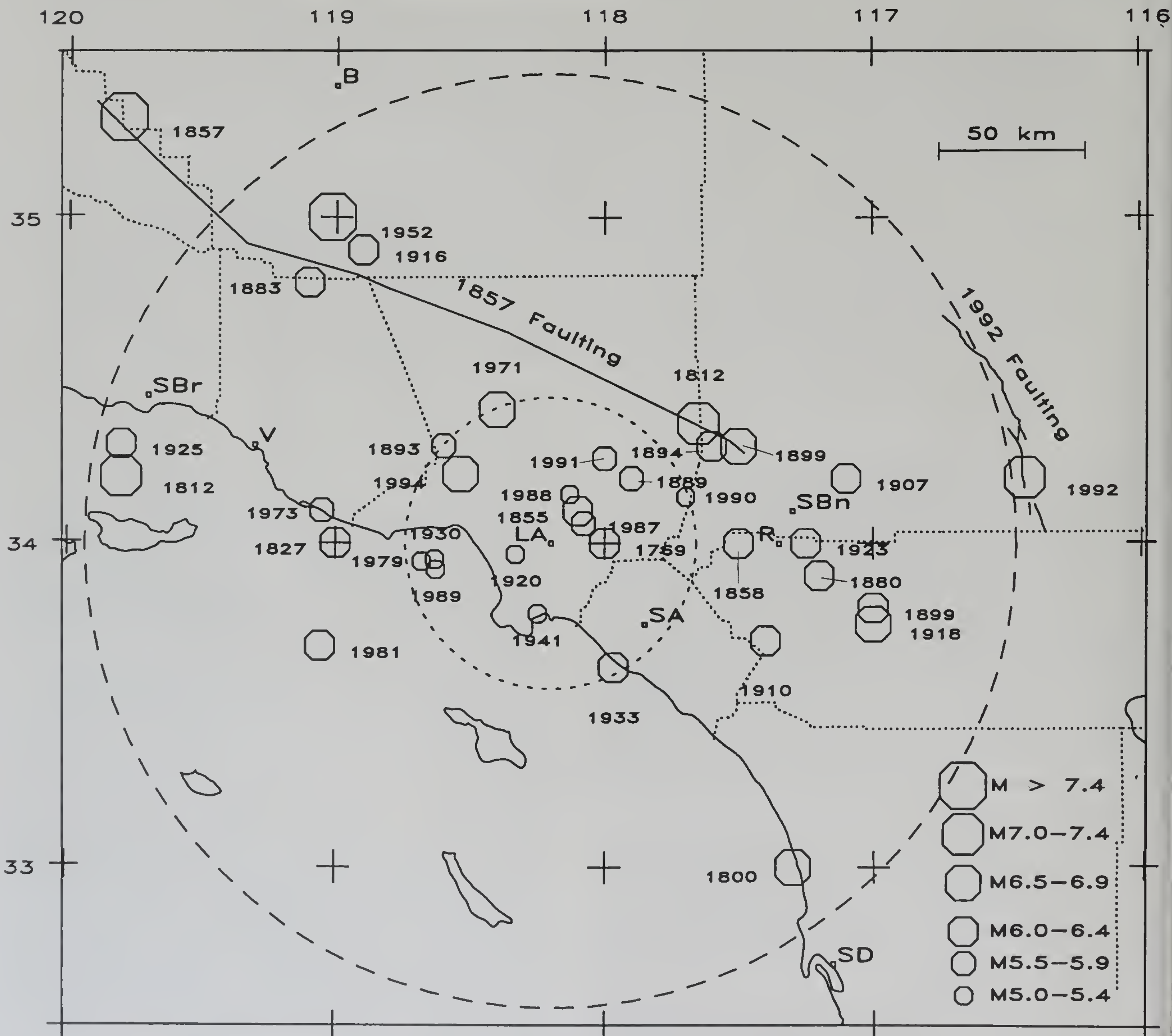


Figure 1. Epicenters of earthquakes identified since 1769 of M≥6 within 160 km (outer circle) of Los Angeles (34.0° N, 118.2° W), and M≥5 within 50 km (inner circle) of Los Angeles. Surface faulting is shown for the major 1857 and 1992 earthquakes that initiated beyond 160 km from Los Angeles. Towns shown are (from west to east) Santa Barbara, (S Br)), Ventura (V), Bakersfield(B), Los Angeles (LA), Santa Ana (SA), Riverside (R), San Bernardino (S Bn), and San Diego (SD).

1932) information are Townley and Allen (1939), Toppozada and others (1978, 1981), Ellsworth (1990), and Stover and Coffman (1993).

1769.7.28 - Los Angeles-Santa Ana area, about M 6?

Members of the Portola expedition felt a sharp earthquake near the Santa Ana River about 50 km SE of Los Angeles. For the next week, aftershocks were felt daily as the party moved westward through Los Angeles. No aftershocks were mentioned as the party travelled northward through San Fernando Valley. An epicenter near the Los Angeles-Orange county border is assumed on the map, but an epicenter as far away as the San Jacinto or San Andreas faults is also possible.

1800.11.22 - San Juan Capistrano-San Diego area, about M 6.5.

Adobe walls were cracked at San Juan Capistrano and at San Diego. An earthquake of M>6.5 is required to damage these two missions that are 90 km apart. Lacking any other information, the epicenter is assumed to be halfway between the two locations. Nearby candidate sources include the Rose Canyon and Elsinore faults.

1803.? – Vicinity of Mission San Gabriel?, about M 6?

The San Gabriel Mission report dated 21 February 1805, for the years 1803-1804, states that the church domes were cracked and split by a violent earthquake, and that they should be destroyed and rebuilt with wood and tiles instead of masonry. No other reports are available for this earthquake, and an epicenter is not estimated or shown in Figure 1. The event is listed in Table 1 and shown in Figure 2.

1812.12.8 - Probably San Andreas Fault, about M 7.

The church at San Juan Capistrano collapsed killing 40 people, and damage was sustained at San Gabriel and probably San Fernando. Trauma (dated as 1812 by dendrochronology) to trees growing on the San Andreas Fault (SAF) at Wrightwood suggests the SAF as the source of the earthquake (Jacoby and others, 1988).

1812.12.21 - Santa Barbara vicinity, about M 7.

Missions Purisima Concepcion, Santa Inez, Santa Barbara, San Buenaventura and possibly San Fernando were significantly damaged, although the latter was likely damaged in the earthquake of December 8th (above). Strong aftershocks were felt at Santa Barbara and San Buenaventura for more than ten days.

1827.9.24 - Ventura County area, about M 6.

Buildings at Mission San Buenaventura were damaged, and people in Los Angeles rushed outdoors. This suggests an event of about M 6, perhaps east of San Buenaventura. An approximate epicenter at 34°N, 119°W was assumed. There is no other information to suggest which of the numerous faults in the vicinity of Ventura was the source of this event.

1855.7.10 - Los Angeles, about M 6?

Many buildings in downtown Los Angeles and San Gabriel were severely damaged and the bells at Mission San Gabriel were thrown down. This suggests a local event of about M 6, which was strongly damaging to the building inventory in Los Angeles and San Gabriel.

1857.1.9 - San Andreas Fault, M 7.8.

Extensive faulting from southern Monterey County to San Bernardino County. Some houses were cracked in downtown Los Angeles (60 km from the fault), and damage was stronger in San Fernando (40 km from the fault) according to Agnew and Sieh (1978). In downtown Los Angeles damage to the rigid adobe buildings of the period was less in this M 7.8 earthquake located 60 km or more away than in the local M 6 event of 1855.

1858.12.16 - San Bernardino area?, about M6?

A house partially collapsed in San Bernardino. The event was reported felt in Los Angeles. This is a **possible aftershock of the 1857 event.**

1880.12.19 - Area south of San Bernardino **(newly identified event)**, about M 6.

Townley and Allen (1939) state only that this event was felt from Los Angeles to San Diego. With no other information, this event was not located by Toppozada and others (1981). Recently available information from the Monthly Weather Review Report confirms these felt reports and adds that "at San Bernardino the court-house walls were cracked from base to eaves." This makes it possible to estimate an approximate epicenter to the south of San Bernardino by comparing the effects to the felt intensity effects of the neighboring earthquakes of 1858, 1889, 1910, 1918, and 1923. A possible foreshock of M~5 on November 21 broke dishes in San Bernardino.

1883.9.5 - Ventura-Kern County border area **(moved from Santa Barbara Channel)**, about M 6.

Recently uncovered felt reports from Kern and Ventura counties and comparison to the intensity map of the 1916.10.23 Tejon Pass event (Toppozada and Parke, 1982) indicate that the 1883 event was centered near the SAF rather than in the Santa Barbara Channel as suggested by Toppozada and others (1981). It caused alarm at San Emigdio Ranch south of Bakersfield and cracked plastering at Santa Barbara. At Ventura "books, vases, and other loose articles were shaken from their mooring."

Table 1. Earthquakes of M 6 within 160 km of Los Angeles , and M 5 within 50 km of Los Angeles (34.0°N, 118.2°W).

YEAR	MONTH/DAY	LAT° N	LONG° W	MAG
1769	07/28	34.0	118.0	6?
1800	11/22	33.0	117.3	6.5
1803†	---	---	---	6?
1812	12/08	34.37	117.65	7
1812	12/21	34.2	119.8	7
1827	09/24	34.0	119.0	6?
1855	07/10	34.1	118.1	6?
1857	01/09	35.3	119.8	7.8
1858	12/16	34.0	117.5	6?
1880	12/19	33.9	117.2	6
1883	09/05	34.8	119.1	6
1889	08/28	34.2	117.9	5.5
1893	04/04	34.3	118.6	6
1894	07/30	34.3	117.6	6
1899	07/22	34.3	117.5	6.5
1899	12/25	33.8	117.0	6.4
1907	09/20	34.2	117.1	6
1910	05/15	33.7	117.4	6
1916	10/23	34.9	118.9	5.7
1918	04/21	33.75	117.0	6.8
1920	06/21	33.97	118.33	4.9*
1923	07/23	34.0	117.25	6.2
1925	06/29	34.3	119.8	6.3
1930	08/31	33.95	118.63	5.2
1933	03/11	33.62	117.97	6.4
1941	11/14	33.78	118.25	4.8*
1952	07/21	33.0	119.02	7.5
1971	02/09	34.41	118.40	6.7
1973	02/21	34.1	119.05	5.9
1979	01/01	33.94	118.68	5.2
1981	09/04	33.7	119.06	6.0
1987	10/01	34.06	118.08	5.9
1988	12/03	34.15	118.13	5.0
1989	01/19	33.92	118.63	5.0
1990	02/28	34.14	117.68	5.3
1991	06/28	34.26	118.0	5.8
1992	06/28	34.2	116.43	7.3
1994	01/17	34.21	118.54	6.7

†Vicinity of Mission San Gabriel?
*Treated as M~5.0 in Figures 1 and 2.

1889.8.28 - Near Monrovia, about M 5 to 5.5.

The felt effects in southern California counties of this event are similar to those of the 1991 Sierra Madre earthquake described below. For example in Monrovia, wall plaster, glass, and china were damaged in 1889, and chimneys broke in 1991. Comparing the felt effects of the 1889 event described by Toppozada and others (1981) with those of the 1991 event described by Stover and Reagor (1991) suggests that the 1889 epicenter be moved about 10 km north toward the 1991 epicenter, and the magnitude be increased to M 5.5.

1893.4.4 - San Fernando Valley, about M 5.5 to 5.9.

The effects of this earthquake were comparable in distribution, but lower in intensity to those of the 1971 San Fernando and 1994 Northridge earthquakes, suggesting a source near San Fernando Valley. At Newhall Ranch an adobe house was shaken down. At Saugus and

Los Angeles chimneys were damaged. At Fillmore and at Pasadena plastering was severely damaged. In the Simi Hills frequent aftershocks were felt for weeks.

1894.7.30 - San Gabriel Mountains north of Pomona, about M 6.

Plaster cracked in Riverside and San Bernardino and some fell. A few panes of glass broke in Los Angeles. The intensity pattern resembles that of the 1899.7.22 event described below (Toppozada and others, 1981), and the M 5.2 Lytle Creek event of 1970.9.12.

1899.7.22 - Cajon Pass area, about M 6.5.

Walls and chimneys were severely cracked at San Bernardino, Riverside, Highland, Cucamonga and Los Angeles. A foreshock of about M 5.5 occurred 20 hours earlier.

1899.12.25 - San Jacinto-Hemet area, M 6.4.

Severe damage to wood frame and brick houses at San Jacinto and Hemet. In Pomona plaster fell at many places. At Los Angeles windows were broken.

1907.9.20 - San Bernardino Mountains area, about M 6.

Walls were cracked and dishes broken at San Bernardino.

1910.5.15 - Lake Elsinore area, about M 6.

Chimneys were damaged in Riverside, Corona and Temescal.

1916.10.23 - Tejon Pass area, about M 5.3 to 6.0.

At the Gorman store nearly all the stock of groceries was thrown from the shelves.

1918.4.21 - San Jacinto-Hemet area, M 6.8.

This earthquake was comparable to the December 1899 event in location and magnitude. Buildings were thrown down at San Jacinto and Hemet. Chimneys fell at Riverside and Redlands.

1920.6.21 - Inglewood area, M 4.9 (considered M~5 in Figures 1 and 2).

Walls of buildings fell out into the streets at Inglewood.

1923.7.23 - Loma Linda area, M 6.0

At San Bernardino chimneys fell and walls were badly cracked.

1925.6.29 - Santa Barbara area, M 6.3.

Thirteen lives were lost and about $8 million in damage occurred, mostly in Santa Barbara and nearby towns.

1930.8.31 - Santa Monica Bay, M 5.2.

At Venice a cornice fell. At Los Angeles plaster fell and dishes broke. Tsunami waves induced by submarine slumping occurred between Santa Monica and Redondo Beach (Lander and Others, 1993, p. 67)

1933.3.11 - Newport-Inglewood Fault zone, M 6.4.

Serious damage to weak masonry structures from Laguna Beach to Los Angeles. Property damage was estimated at $40 million, and 115 people were killed.

1941.11.14 - Gardena-Torrance area, M 4.8 (considered M~5 in Figures 1 and 2).

At Torrance most buildings were damaged and a school was condemned. At Gardena a school was also condemned. The M 5.4 for this event was revised to M 4.8 by Hutton and Jones (1993). Three weeks earlier a similar event of M 4.8 cracked walls and broke windows at Gardena and Compton.

1952.7.21 - White Wolf Fault, M 7.5.

Serious damage in Kern County, where 12 lives were lost and property damage was estimated at $60 million. In Los Angeles 135 km from the epicenter, damage was nonstructural but extensive, and was restricted to buildings of 6 to 12 stories high. The modern structures of more than 20 stories high did not exist in 1952.

1971.2.9 - San Fernando, M 6.7.

This event took 65 lives, injured 2,000 people, and caused $505 million in property damage.

1973.2.21 - Near Point Mugu, M 5.9.

Severe damage to unreinforced brick buildings in Oxnard. This event is more than 50 km from Los Angeles but is included in the analysis because it is about M 6.

1979.1.1 - Near Malibu, M 5.2.

Broke windows in Culver City, Malibu, Santa Monica, Tustin and Venice.

1981.9.4 - 45 km south of Point Mugu, M 6.0.

Broke windows in Marina del Rey and rendered elevators inoperative in Los Angeles.

1987.10.1 - Whittier Narrows, M 5.9.

This urban event took 8 lives, injured several hundred people and caused $358 million property damage.

1988.12.3 - Pasadena, M 5.0.

Windows were broken at Whittier. Several bricks were knocked down at Mission San Gabriel.

1989.1.19 - Offshore from Malibu, M 5.0.

Broke windows and damaged stock in stores in Hollywood, Malibu and Monterey Park.

1990.2.28 - North of Pomona, M 5.3.

About $13 million in property damage in the Upland-Pomona area.

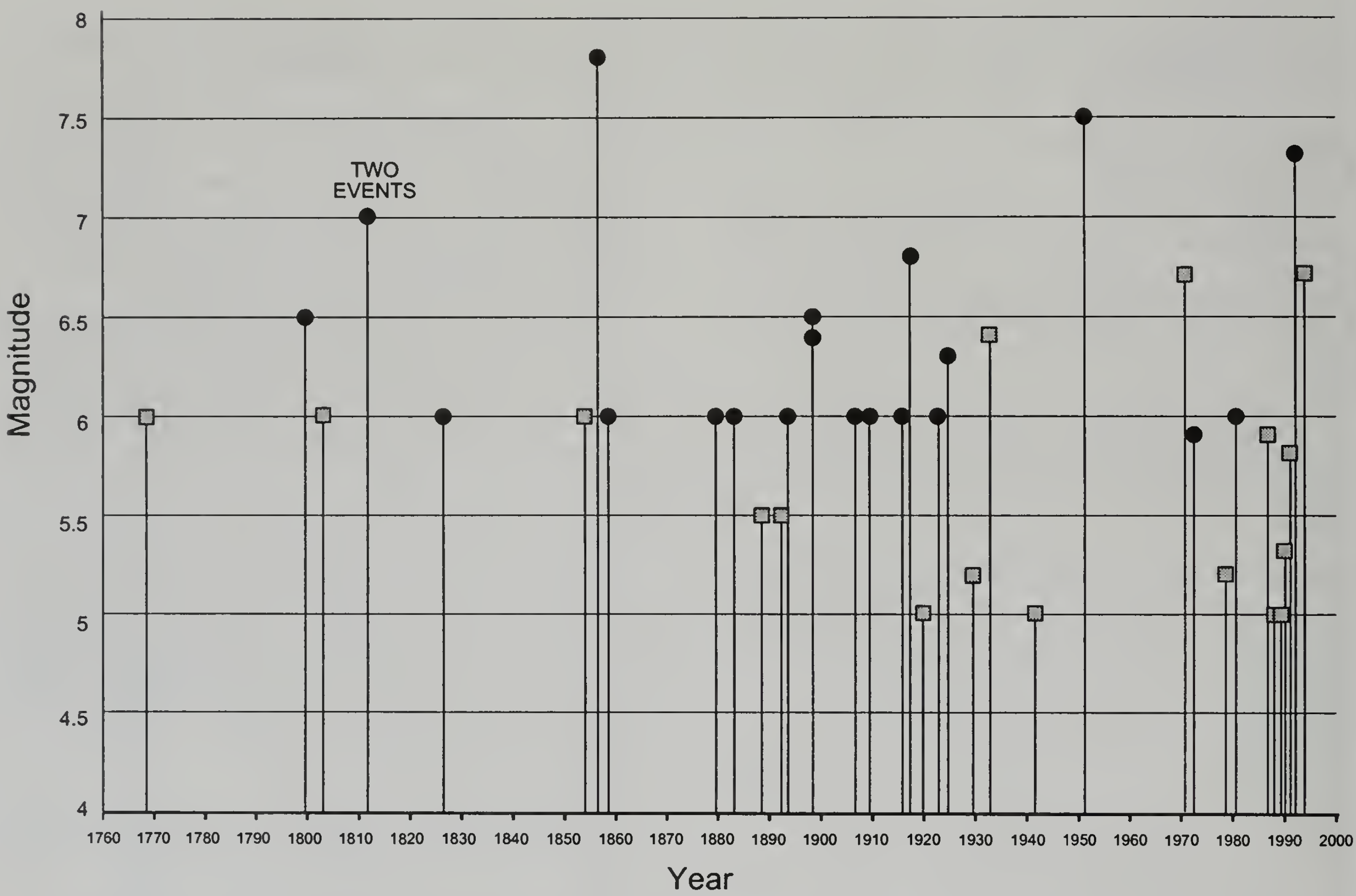


Figure 2. Temporal and magnitude distribution of earthquakes identified since 1769 of M≥6 within 160 km of Los Angeles, and M≥5 within 50 km of Los Angeles. Events located within 50 km of Los Angeles are indicated by bars capped with squares. Events located from 50 to 160 km of Los Angeles are indicated by bars capped with circles.

1991.6.28 - Sierra Madre, M 5.8.

This suburban earthquake caused one death, and $33.5 million in property damage, mainly in Arcadia and Monrovia (Stover and Reagor, 1991). This event appears to have similar felt effects to the 1889 event described above.

1992.6.28 - Landers area, M 7.3.

This major earthquake in the Mojave Desert caused one death, and about $90 million in property damage, mainly in San Bernardino County.

1994.1.17 - Northridge area, M 6.7.

Fifty-nine lives lost and about $20 billion in damage.

SEISMICITY

The temporal distribution of the earthquakes and their magnitudes from Table 1 and Figure 1 are shown in Figure 2.

Before 1889 Figure 2 identifies no events of M<6, due mainly to the lack of adequate records. Before that time adequate records are only available for earthquakes that were destructive or significant to the sparse existing population. The 1769 event was well reported by the Spanish expeditionary party of Gaspar de Portola because of its severity and the extensive nature of its aftershock sequence. The events of 1800, 1803, 1812 (two) and 1827 damaged various Missions between San

Diego and Santa Barbara. The moderate local Los Angeles earthquake of 1855 was more destructive to the rigid adobe buildings in Los Angeles at the time than the major 1857 event that occurred 60 km or more from downtown Los Angeles (see Earthquake Descriptions). The 1858 earthquake was destructive at San Bernardino near the southern end of the major 1857 faulting, and was possibly a late aftershock of that event. The 1883 event epicenter was moved from the Santa Barbara Channel (Toppozada and others, 1981) to the Ventura-Kern county border area, based on recently uncovered felt reports. This move illustrates the critical effects of the scarcity of reporting locations in the early 1880s. The newly identified 1880 event was felt from Los Angeles to San Diego, and recently available reports indicate damage at San Bernardino.

From 1889 to 1933 ten mainshocks of M 6 or greater occurred, but only one epicenter was within 50 km of downtown Los Angeles (bar capped by square in Figure 2). The seismicity was dominated mainly by the San Jacinto-Hemet events of 1899 and 1918, and the San Bernardino region events of 1894, 1899, 1907, and 1923 (Figures 1 and 2). The most destructive earthquake from 1889 to 1933 was the 1933 Long Beach earthquake in the urban area along the Newport-Inglewood Fault zone. This fault zone was also the probable source of the 1920 and 1941 events. Other damaging earthquakes within 50 km of Los Angeles (indicated by bars capped with squares in Figure 2) occurred in 1889 near Monrovia, 1893 near San Fernando, and 1930 in Santa Monica Bay.

From 1934 to 1970 only one mainshock of M>5 occurred. The major 1952 earthquake was preceded and followed by the longest periods (about 19 years) with no M>5 events since the 1880s (Figure 2). Periods of 20 to 30 years without events of M>6 occur before 1880 because of incompleteness of the earthquake record.

From 1971 through 1994 there was an increase in seismicity, particularly within 50 km of Los Angeles as seen from the bars capped with squares in Figure 2. Out of the three M>6 mainshocks that occurred in this period, two were centered within 50 km of downtown Los Angeles. The major 1992 Landers event (M 7.3) and its largest aftershock near Big Bear Lake occurred away from densely populated centers, resulting in minimal death and destruction. In fact, the much smaller but urban Whittier Narrows (M 5.9) event of 1987 resulted in larger losses (see Earthquake Descriptions). The greatest losses resulted from the strong 1971 and 1994 earthquakes in San Fernando Valley. There was a historical precedent of a damaging earthquake in this area in 1893 (see Earthquake Descriptions). The 1994, 1971 and 1893 events comprise three out of a total of only seven mainshocks of M$\geq$5.5 that have occurred within 50 km of Los Angeles since 1880 (indicated by bars capped with squares in Figure 2, assuming M 5.5 for the 1889 event as indicated in Earthquake Descriptions). This is consistent with the high probabilistic seismic hazard assessed for the San Fernando Valley area (e.g. Petersen and others, 1995; Working Group on California Earthquake Probabilities, 1995). The remaining four M>5.5 Los Angeles events occurred in 1991 north of Monrovia and Sierra Madre, 1987 near Whittier Narrows, 1933 near Long Beach, and 1889 north of Monrovia. The 1889 and 1991 events north of Monrovia are compared under Earthquake Descriptions.

The seismic period that started in 1971 is dominated by events within 50 km of Los Angeles. The 1971 through 1994 period of increased seismicity is shorter than the 1880 to 1933 seismic period, which is probably longer than 53 years because the record before 1880 is incomplete. Long term implications of the increased seismicity within 50 km of Los Angeles since 1987 are not readily apparent from the short historical record depicted in Figure 2. The increased seismicity warrants diligent preparedness and mitigation efforts.

Local versus Distant Earthquake Effects

In Los Angeles the most destructive earthquakes have been local events of M<7 occurring within 50 km of downtown, as indicated under Earthquake Descriptions. These include the M 5.5 to 6.7 events of 1855, 1893, 1933, 1971, 1987, 1991 and 1994. For example the local Los Angeles area event in 1855 of about M 6 was more destructive, at least to the low rigid adobe buildings of the period in Los Angeles, than the more distant M 7.8 earthquake of 1857. A repeat of the great 1857 earthquake would probably be more destructive today than a repeat of the 1855 event, particularly to the modern high rise buildings that would respond more strongly to long period motion.

Completeness of the Earthquake Record

The dearth of M~6 or greater events before 1880 suggests that the record is incomplete before that time (Figure 2). This is due in large part to the scarcity of newspaper coverage and other written records in southern California at that time. Even though many newspapers were published in the San Francisco-Sacramento area in the 1850s during the Gold Rush (Toppozada and others, 1981), it was not until about 1880 that at least 6 newspapers were published within 160 km of Los Angeles (Agnew, 1991). Before that time the only M$\geq$6 events identified are those that were potentially destructive in Los Angeles and surroundings. The 1800, 1803, 1812 (two events), and 1827 earthquakes damaged various Franciscan Mission buildings and were reported in Mission documents. The scant information reported in Mission documents ceased after the missions were secularized

in 1833-1844. During the next 47 years until 1880, the only earthquakes identified are the great 1857 event (M 7.8), and the 1855 and 1858 events that were destructive in Los Angeles and San Bernardino, respectively. It is possible that the lack of M 6 events between 1858 and 1880 is post-seismic quiescence following the great 1857 earthquake. Such quiescence was observed for about 50 years following the great 1906 San Francisco earthquake. However, it is more likely that the lack of identified M≥6 events between 1858 and 1880 around Los Angeles was due to inadequate records. The increase in the number of identified events starting in 1880 (Figure 2) coincides closely with the increase in population and published newspapers in southern California (Toppozada and others,1981; Agnew, 1991).

SUMMARY

The history of M~6 earthquakes within 160 km (100 mi) of Los Angeles is incomplete before 1880, due to the lack of adequate records. From 1880 to 1970, M>5.5 earthquakes have occurred dominantly more than 50 km from Los Angeles, with the notable exception of the 1933 Long Beach earthquake. Starting in 1971, M>5.5 earthquakes have occurred more frequently within 50 km of Los Angeles. The increased seismicity near Los Angeles warrants diligent preparedness and mitigation efforts.

The most destructive earthquakes in Los Angeles have been local events of M<7 occurring within 50 km of downtown. The 1857 earthquake of M 7.8 was 60 km or more from Los Angeles, and caused less damage to the low rigid adobe buildings of the time than did a local Los Angeles event of about M 6 in 1855.

The 1991 Sierra Madre event of M 5.8 that was damaging in Monrovia and surroundings had a precedent of M 5.5 in 1889. The 1971 and 1994 events that were destructive in San Fernando Valley had a smaller damaging precedent of M 5.5 to 5.9 in 1893.

ACKNOWLEDGMENTS

Chris Cramer and Tai Le assisted with preparing Figures 1 and 2. Claudia Hallstrom searched for newspaper reports of the 1880 and 1883 events. Critical review was provided by Chris Cramer, Egill Hauksson, Mark Petersen, and Michael Reichle.

REFERENCES

Agnew, D.C., 1991, How complete is the pre-instrumental record of earthquakes in southern California, *in* Abbott, P.L., and Elliott, W.J., eds., Environmental Perils in San Diego Region: Geological Society of America, San Diego Association of Geologists.

Agnew, D.C., and Sieh, K.E., 1978, A documentary study of the felt effects of the great California earthquake of 1857: Bulletin Seismological Society of America, v. 68, no. 6, p. 1717-1729.

Ellsworth, W.L., 1990, Earthquake history, 1769-1989 *in* Wallace, R.E., ed., The San Andreas Fault System, California: U.S. Geological Survey Professional Paper 1515, 283 p.

Hutton, L.K., and Jones, L.M., 1993, Local magnitudes and apparent variations in seismicity rates in southern California: Bulletin Seismological Society of America, v. 83, p. 313-329.

Jacoby, G.C., Sheppard, P.R., and Sieh, K.E., 1988, Irregular recurrence of large earthquakes along the San Andreas fault, Evidence from trees: Science, v. 241, no. 4862, p. 196-199.

Lander, J.F., Lockridge, PIA., and Kozuch, M.J., 1993, Tsunamis affecting the west coast of the United States: National Geophysical Data Center Key to Geophysical Records Documentation, no. 29, 242 p.

Petersen, M.D., Cramer, C.H., Bryant, W.A., Reichle, M.S., and Toppozada, T.R., 1995, Preliminary Assessment for Los Angeles, Ventura, and Orange counties, California, affected by the January 17, 1994 Northridge earthquake, submitted to Bulletin Seismological Society of America.

Stover, C.W., and Coffman, J.F., 1993, Seismicity of the United States, 1568-1984 (Revised): U.S. Geological Survey Professional Paper 1527, 418 p.

Stover, C.W., and Reagor, G.B., 1991, Preliminary isoseismal map for the Sierra Madre, California, earthquake of June 28, 1991: U.S. Geological Survey Open-File Report 91-388, 16 p.

Toppozada, T.R., and Parke, D.L., 1982, Areas damaged by California earthquakes: California Department of Conservation, Division of Mines and Geology, Open-File Report 82-17, 65 p.

Toppozada, T.R., Parke, D.L., and Higgins, C.T., 1978, Seismicity of California 1900-1931: California Department of Conservation, Division of Mines and Geology, Special Report 135, 39 p.

Toppozada, T.R., Real, C.R., and Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes: California Department of Conservation, Division of Mines and Geology, Open-File Report 81-11 SAC, 182 p.

Townley, S.D., and Allen, M.W., 1939, Descriptive catalog of earthquakes of the Pacific coast of the United States 1769 to 1928: Bulletin Seismological Society of America, v. 29, no. 1, p. 1-297.

Working Group on California Earthquake Probabilities, 1995, Seismic hazards in southern California – probable earthquakes, 1994 to 2024: Bulletin Seismological Society of America, v. 85, no. 2, p. 379-439.

Hauksson, Egill, 1995, Seismological overview of the 1994 Northridge earthquake sequence in California *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 17-38.

SEISMOLOGICAL OVERVIEW OF THE 1994 NORTHRIDGE EARTHQUAKE SEQUENCE IN CALIFORNIA

by

Egill Hauksson[1]

ABSTRACT

The Northridge earthquake occurred on January 17, 1994 at 4:30 a.m. Pacific Standard Time in the San Fernando Valley. The hypocenter was about 32 km west-northwest of Los Angeles at a relatively deep focal depth of 19 km. The moment magnitude for the Northridge earthquake is M_w6.7. The 1994 Northridge earthquake occurred on a south-southwest dipping thrust ramp beneath the San Fernando Valley and thus reemphasized the seismic hazard of concealed faults in the greater Los Angeles region. The occurrence of the Northridge earthquake also shows that this high rate of seismicity along the northern edge of the Los Angeles basin is continuing. The mainshock was followed by an energetic aftershock sequence. Eight aftershocks of M 5.0 and 48 aftershocks of 4 M<5 occurred between January 17 and September 30, 1994. The aftershocks extend over most of the western San Fernando Valley and Santa Susana Mountains. The 1971 San Fernando and the 1994 Northridge earthquakes ruptured partially abutting fault surfaces on opposite sides of a ridge. Both earthquakes accommodated north-south contractional deformation of the Transverse Ranges.

INTRODUCTION

The 1994 M_w6.7 Northridge earthquake is the latest in a series of moderate-sized to large earthquakes to occur in the north Los Angeles region (Hauksson, 1992). The earthquake occurred on a south-southwest dipping thrust ramp located to the southwest of the west end of the Sierra Madre Fault system and to the south of the east end of the Santa Susana, San Cayetano, and Oak Ridge fault systems (Figure 1A; Proctor and others, 1972; Yeats, 1981; Çemen, 1989). The occurrence of the earthquake away from mapped surface fault structures demonstrated the complex three-dimensional nature of the tectonics in this region (Hauksson and others, 1995). Like all of the significant earthquakes that have occurred since the 1920s in southern California, the Northridge earthquake thus provided new insights into the regional tectonics and seismological aspects of such sequences.

The rate of tectonic deformation across the northern Los Angeles area and the central Transverse Ranges is relatively high (Donnellan and others, 1993; and Hudnut and others, 1994). Global Positioning System (GPS) measurements across the Ventura basin, 30 km northwest of the Northridge rupture, show north-south shortening of 7-10 mm/yr, that may be accommodated by the San Cayetano, Red Mountain, and Oak Ridge faults (Donnellan and others, 1993). Similar measurements across the Los Angeles basin indicate shortening rates of 5-10 mm/yr (Feigl and others, 1993).

The long-term (1978 to 1994) background seismicity in the central Transverse Ranges is dominated by aftershocks of the 1971 M_w6.7 San Fernando earthquake (Figure 2). A few of the large clusters in the north Los Angeles region are also earlier mainshock-aftershock sequences (Hauksson, 1990). To the south of the 1971

[1]Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California

aftershock zone, the seismicity in the San Fernando Valley region has been characterized by a low level background seismic activity that did not illuminate individual or distinctive fault structures beneath the valley. Both to the north and south of the valley, tectonic models of north-dipping surficial reverse faults or concealed north-dipping thrust ramps were supported primarily by geologic data and in a few cases by the background seismicity (Namson and Davis, 1992; Hauksson, 1990). In comparison, the 1994 Northridge sequence extended across a wide area and provided new data for the valley and the eastern part of the Santa Susana Mountains. Both the west and east edges of the 1994 aftershock zone form distinct north-northeast trends and appear to coincide with some of the similar trends in the background seismicity. Future analysis of the background seismicity thus may contribute to understanding of possible segmentation of concealed faults.

The two largest earthquakes to occur in this region during this century are the 1971 San Fernando and the 1994 Northridge earthquakes (Figure 1). Although the Northridge earthquake was the same size as the 1971 San Fernando earthquake (M_w6.7), it was much more damaging in part because of its location beneath the heavily populated San Fernando Valley and its closer proximity to other communities in the Los Angeles basin. In map view the aftershock zones of both earthquakes overlap, suggesting that the causative thrust faults are at least geometrically related.

The 1994 Northridge earthquake and its aftershocks illuminate for the first time a south dipping thrust ramp beneath the San Fernando Valley, which serves to emphasize the hazard associated with undetected thrust faults in this region. In this paper we synthesize the seismological observations from the Northridge earthquake sequence to facilitate our understanding of the role these tectonic structures play in the regional crustal deformation of the compressional zone of the central Transverse Ranges.

EARTHQUAKE HISTORY 1920 -1994

Since 1920, fifteen moderate-sized to large (M4.8-6.7) mainshock-aftershock sequences have occurred in the greater Los Angeles area (Figure 1 and Table 1). These earthquakes are associated with many low slip-rate, late Quaternary faults distributed throughout the region (Ziony and Yerkes, 1985; Ziony and Jones, 1989). Because surface rupture has only occurred once since the 1920s, during the 1971 San Fernando earthquake, the association between a mainshock hypocenter and a nearby fault typically has been inferred from the mainshock focal mechanism and the distribution of aftershocks. They have been associated with surficial reverse faults, right-lateral or left-lateral strike-slip faults, and concealed thrust ramps (Hauksson, 1990), reflecting the merging of the strike-slip deformation of the Peninsular Ranges with the contractional deformation of the Transverse Ranges.

Table 1. Significant earthquakes in the greater Los Angeles basin and adjacent offshore region.

DATE	Earthquake	Mo *10^{25} (dyne-cm)	M_L old	M_L new[1)]	M_w	M	Latitude	Longitude	Depth (km)	FM[2)]	References
1920 June 21	Inglewood		4.9			4.9	34° 58'	118°20'			Taber (1920)
1930 Aug. 30	Santa Monica Bay		5.2			5.2	34°01.8'	118°38.6'			Gutenberg et al. (1932)
1933 Mar. 10	Long Beach	5	6.3[3)]		6.4	6.4	33°39.54'	117° 58.30'	10±2	r-ss	Wood (1933); Hauksson & Gross (1991)
1938 May 31	Elsinore Fault		5.5	5.2		5.2	33° 41.9'	117° 30.6'			Hileman et al., (1973)
1941 Oct. 22	Gardena		4.9	4.8		4.8	33° 49.0'	118° 13.0'			Richter (1958)
1941 Nov. 14	Torrance-Gardena		5.4	4.8		4.8	33° 47.0'	118° 15.0'			Richter (1958)
1970 Sept. 12	Lytle Creek	0.1	5.4	5.2		5.2	34° 16.2'	117° 32.4'	09	th	Jones (1984), Thatcher et al. (1975)
1971 Feb. 9	San Fernando	13.0	6.4[3)]		6.7	6.7	34° 25.45'	118° 22.63'	13±3	th	Whitcomb et al. (1973); Heaton (198
1973 Feb. 21	Point Mugu	0.7	5.9[3)]		5.9	5.9	34° 05.95'	119° 02.32'	17±5	th	Stierman & Ellsworth (1976); Bent & Helmberger (1991)
1979 Jan. 1	Malibu		5.0	5.2		5.2	33° 57.78'	118° 41.08'	10±4	th	Hauksson & Saldivar (1986)
1981 Sept. 4	Santa Barbara Isl.	1.1	5.3	5.5	6.0	6.0	33° 40.92'	119° 03.60'	11±5	r-ss	Corbett (1984); Bent (1990)
1987 Oct. 1	Whittier Narrows	1.0	5.9	5.9	5.9	5.9	34° 02.96'	118° 04.86'	15±1	th	Hauksson et al. (1988); Hauksson and Jones (1989)
1988 Dec. 3	Pasadena	0.024	4.9	5.0		5.0	34° 08.47'	118° 07.96'	16±1	l-ss	Jones et. al. (1990); Kanamori et al. (1990)
1989 Jan. 19	Malibu		5.0	5.0		5.0	33° 55.04'	118° 37.37'	14±3	th	Hauksson (1990)
1990 Feb. 28	Upland	0.25	5.2	5.3		5.3	34° 40.92'	119° 03.60'	5±0.5	l-ss	Hauksson & Jones (1991); Dreger & Helmberger (1991a)
1991 June 28	Sierra Madre	0.25	5.4	5.8[4)]		5.8	34° 15.54'	118° 00.06'	12±1	th	Hauksson (1994); Dreger & Helmberger (1991b)
1994 Jan. 17	Northridge	12.0		6.4		6.7	34° 12.55'	118° 32.44'	19±1	th	Scientists of USGS and SCEC (199 Hauksson et al.(1995)

1) Hutton and Jones, (1992); 2) FM: focal mechanism, r-ss: right-lateral strike-slip, l-ss: left-lateral strike-slip, th: thrust faulting;
3) No Wood-Anderson records on scale in southern California; 4) from TERRAscope data, H. Kanamori written communication, 1991.

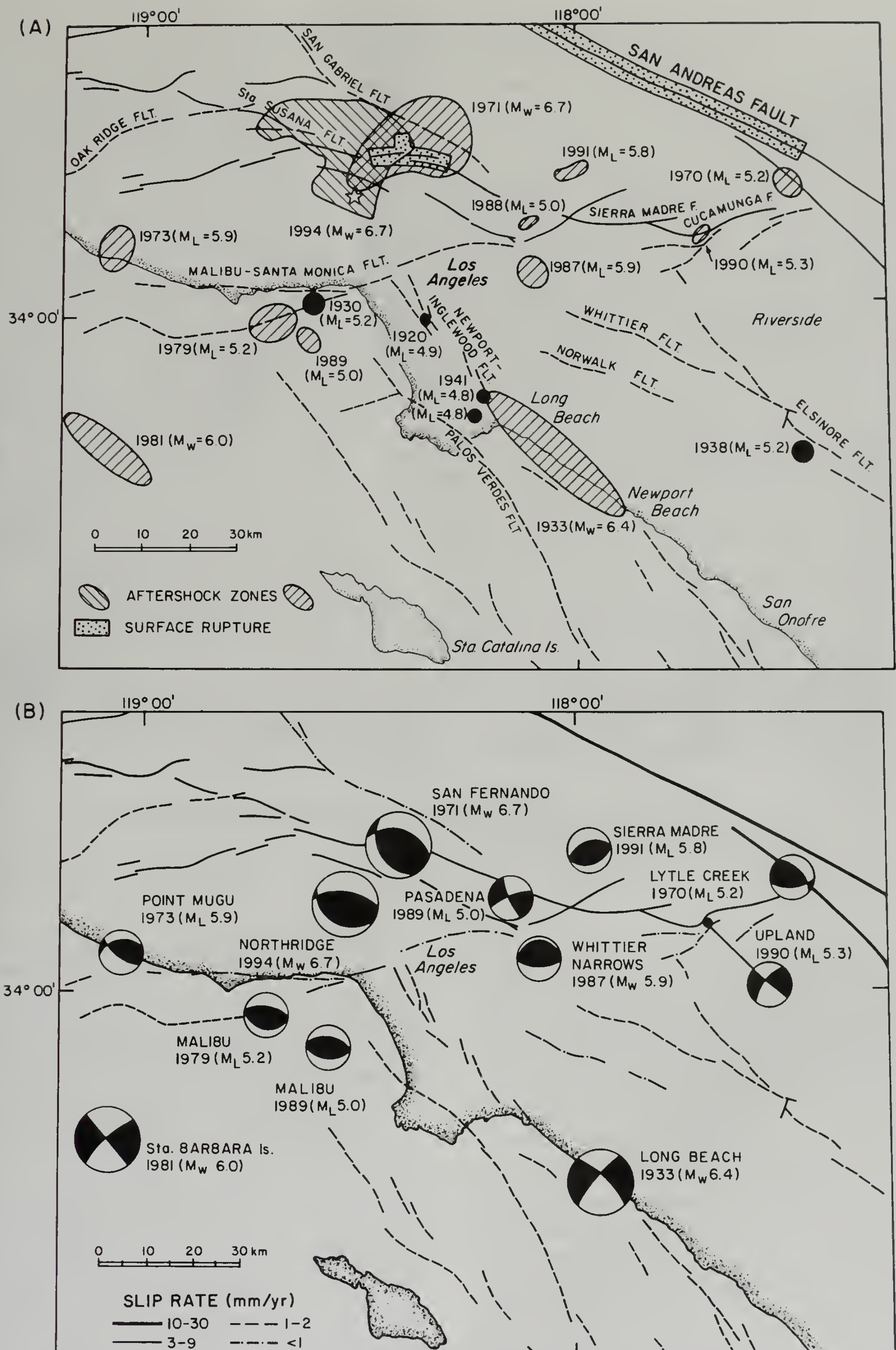


Figure 1. (A) Significant earthquakes of M 4.8 that ha ve occurred in the greater Los Angeles basin area since 1920. Aftershock zones are shaded with cross hatching, including the 1994 Northridge earthquake. Dotted areas indicate surface rupture, including the rupture of the 1857 earthquake along the San Andreas Fault. (B) Lower-hemisphere focal mechanisms for significant earthquakes that have occurred since 1933 in the greater Los Angeles area.

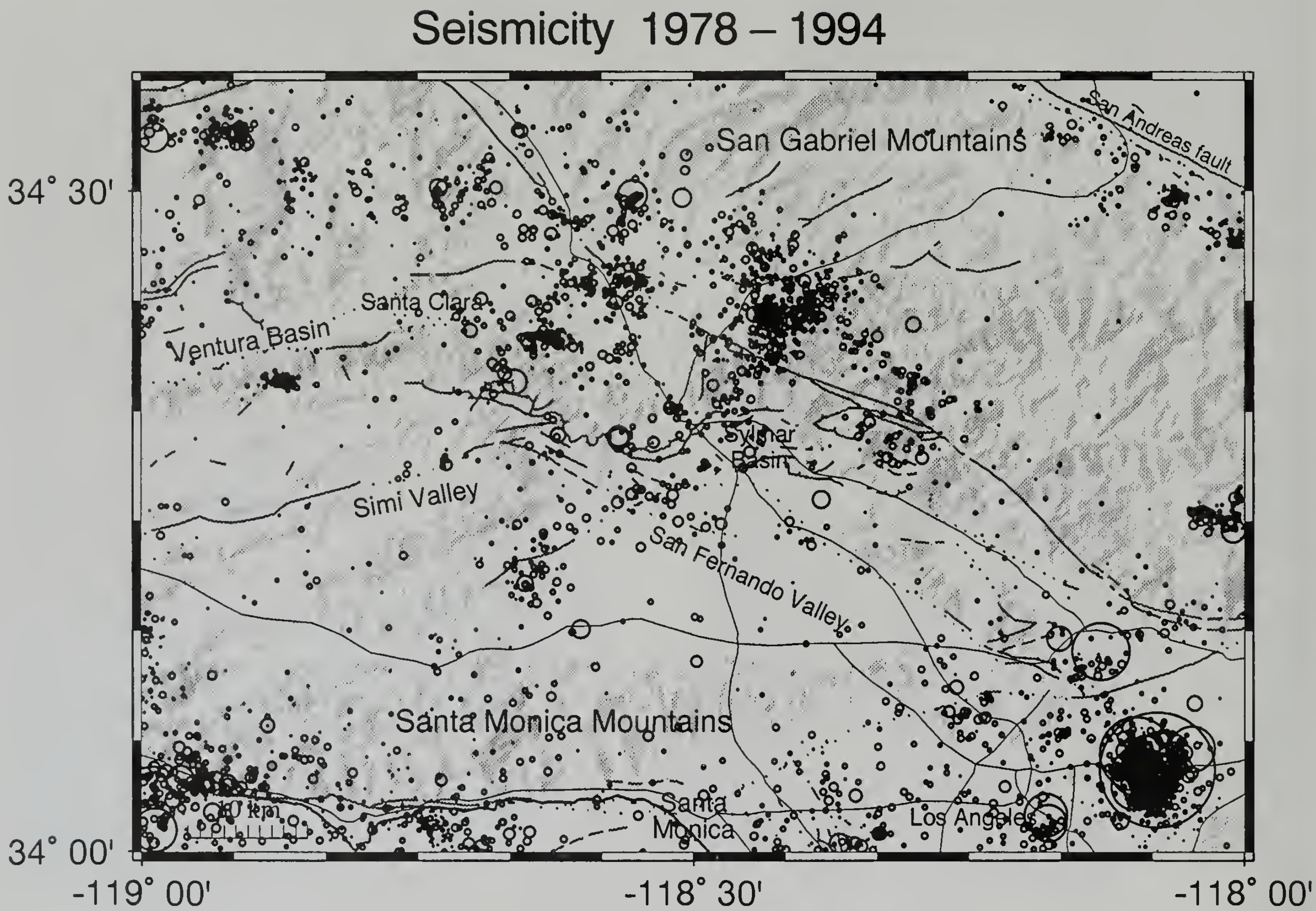


Figure 2. Map of background seismicity in the San Fernando region from 1978 to 1994. Plotted using GMT-software (Wessel and Smith, 1991).

Style of Faulting

In general, the style of faulting determined from focal mechanisms of significant earthquakes is in excellent agreement with the surficially mapped style of faulting on late Quaternary faults. From a data set of twelve (M_L 4.8) events only two focal mechanisms shown in Figure 1B, exhibit right-lateral strike-slip, two events show left-lateral strike-slip movement, and eight events show mostly reverse or thrust faulting.

Before instrumentally determined epicenters became available, the location of an earthquake was inferred from damage patterns or seismic intensities. For instance, some of the first research on Los Angeles basin earthquakes was done by Taber (1920), who was commissioned by the Seismological Society of America to study the 1920 Inglewood (M_L=4.9) earthquake. He attributed the earthquake to slip on the Newport-Inglewood Fault just west of the town of Inglewood, because the event caused concentrated heavy damage in the town.

The 1933 Long Beach earthquake occurred a few years after the installation of the Caltech seismographic network, which at that time consisted of seven stations. The Caltech network and seismographic stations around the world provided sufficient data to show that the event was caused by right-lateral strike-slip movement along the southern segment of the Newport-Inglewood fault, from Newport Beach to the southern edge of the City of Long Beach (Wood, 1933; Richter, 1958; Hauksson and Gross, 1991).

The 1971 San Fernando earthquake is the only historic earthquake in the Los Angeles basin that is known to have caused surface rupture. The focal mechanism showed reverse faulting with a component of left-lateral strike slip motion (Whitcomb and others, 1973). The mainshock caused surface faulting along the 19 km long San Fernando member of the Sierra Madre Fault Zone (Proctor and others, 1972; Heaton and Helmberger, 1979; Heaton, 1982).

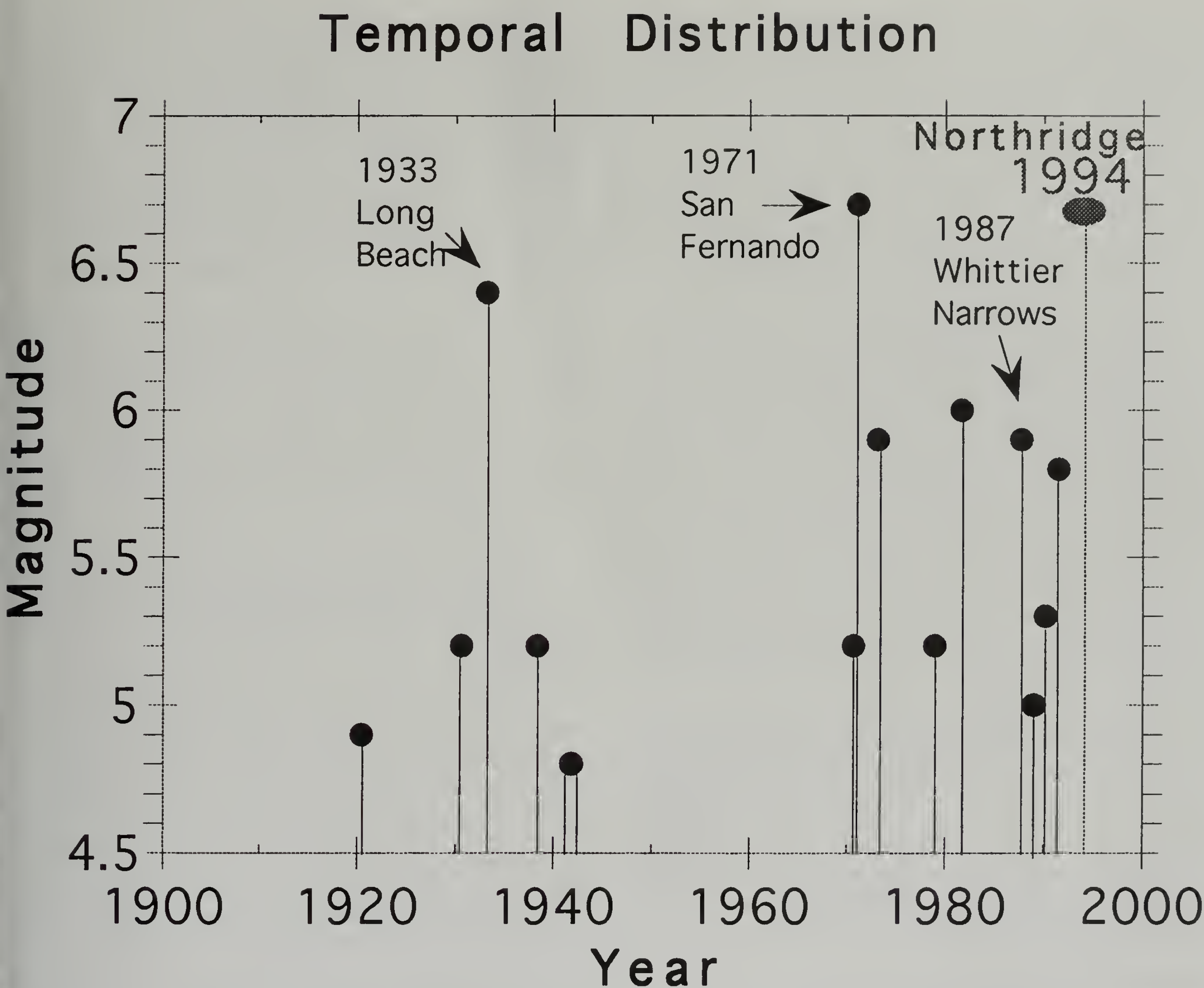


Figure 3. The temporal distribution of (M 4.8) mainshocks in the greater Los Angeles region since 1900.

The 1987 Whittier Narrows earthquake, which occurred on a previously unrecognized concealed thrust fault, showed pure thrust motion on a gently north-dipping plane (Hauksson and Jones, 1989). The 1988 and 1990 Upland earthquakes were caused by left-lateral slip on the San Jose Fault, which splays southwest from the main frontal fault of the central Transverse Ranges (Hauksson and Jones, 1991). These left-lateral faults allow fragments of crustal blocks from the Peninsular Ranges block to move westward around the big bend of the San Andreas Fault..

The 1991 Sierra Madre earthquake was the second moderate-sized event caused by thrust faulting along the Sierra Madre Fault Zone (Hauksson, 1992). Both surficial mapping of the Sierra Madre Fault Zone and the occurrence of the San Fernando and Sierra Madre earthquakes demonstrates that the 110 km-long fault zone is seismically active and may cause damaging earthquakes as large as M7.7 (Crook and others, 1987; Hauksson, 1994).

The 1994 Northridge earthquake is discussed in detail in later sections of this paper.

Temporal and Spatial Distribution

The temporal distribution of M 4.8 earthquakes in the Los Angeles basin is shown in Figure 3. Two periods of activity can be recognized. The first period began in 1920 and ended in 1941. The second period of activity began in 1970 and is still continuing in 1994. These two periods of activity are separated by a 30 year-long period of seismic quiescence when there were no earthquakes of M 4.8 in the greater Los Angeles basin (Hauksson, 1992).

Nearly all of the M 4.8 earthquakes that occurred during the first period of activity from 1920 to 1941 were located along the western edge or in the southwestern part of the Los Angeles basin (Figure 1). The 1933 Long Beach M_w6.4 earthquake was the largest member of the earlier sequence. Two events that occurred in 1941 were also located in the South Bay area. One M_L5.2 event in 1930 was located in Santa Monica Bay and another M_L5.2 in 1938 near the Elsinore Fault. This activity was terminated with two events in 1941 in the South Bay.

The rate of M 4.8 earthquakes during the first period of activity was fairly uniform with one to two events per decade. During the second period of activity the number of earthquakes has increased with time. In the last eight years (1987-1994), six moderate-sized earthquakes have occurred in the Los Angeles area. This is the highest rate of occurrence of moderate-sized earthquakes in the Los Angeles basin reported since the beginning of the CIT/USGS earthquake catalog. Since the early seventies the earthquake activity has mostly remained along the northern edge of the Los Angeles basin. The largest earthquakes to occur in the region so far this century are the 1971 San Fernando and 1994 Northridge earthquakes.

Because the best estimate of the seismicity rate in the near future is assumed to be the current seismicity rate (e.g. Kagan and Jackson, 1994) , the high seismicity rate within the current cluster suggests that more damaging earthquakes will occur over the next decade. A continuation of the current seismicity rate will contribute to releasing the contractional tectonic strain that has accumulated in the western Transverse Ranges over a minimum time interval of 200 years.

Magnitude and Seismic Moment

The most often reported magnitude for an earthquake in the Los Angeles area is the local magnitude (M_L), which is determined from the photographic Wood-Anderson seismograms (Richter, 1958; Hutton and Boore, 1987; Hutton and Jones, 1992). For larger events, data from low gain (amplification of 100 times) instruments are also used. In the case of earthquakes of magnitude 6.0-6.5, however, this magnitude scale may have saturated for the earthquakes that occurred before the installation of TERRAscope in 1990-1991.

"Seismic moment" is a different measure of earthquake size, which is often used for moderate or large-sized earthquakes. A seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the shear modulus of the rocks offset by faulting. Seismic moment is usually determined as part of the inversion of waveforms for the parameters of the earthquake source (Aki and Richards, 1980).

The seismic moment (M_o) of an earthquake is:

$$M_o = \mu A u$$

where μ is shear modulus, A is fault area undergoing slip, and u is the relative slip along the ruptured fault segment.

An empirical relationship has been found between magnitude and seismic moment (M_o) (Hanks and Kanamori, 1979):

$$M = 2/3(\log 10)M_o - 10.7$$

From this relationship moment magnitude (M_w) has been defined. With this more accurate estimate of an earthquake size, seismic moment can be used to estimate magnitude.

In Table 1 three different magnitudes are provided if these are available. The first is the M_L (old) that used to be listed in the CIT/USGS earthquake catalog for southern California. The second is the M_L (new) which are redetermined magnitudes by Hutton and Jones (1992). They reread all the amplitudes and redetermined the magnitudes in a consistent manner for M 4.8 earthquakes in southern California since 1932. The third is the M_w from seismic moments that have been determined in various studies. The fourth magnitude column (M) indicates the currently best available estimates of magnitudes for M 4.8 earthquakes in the Los Angeles basin since 1920.

The local magnitude (M_L old) and the preferred magnitude (M) from Table 1 are plotted in Figure 4 versus seismic moment. All of the data follow a logarithmic relationship, except possibly the 1981 Santa Barbara Island earthquake that appears to have an underestimated magnitude (M_L old). The saturation of the M_L scale can be seen for the 1933 Long Beach, 1971 San Fernando, and 1994 Northridge earthquakes, the three largest events, because the moment magnitudes are systematically higher.

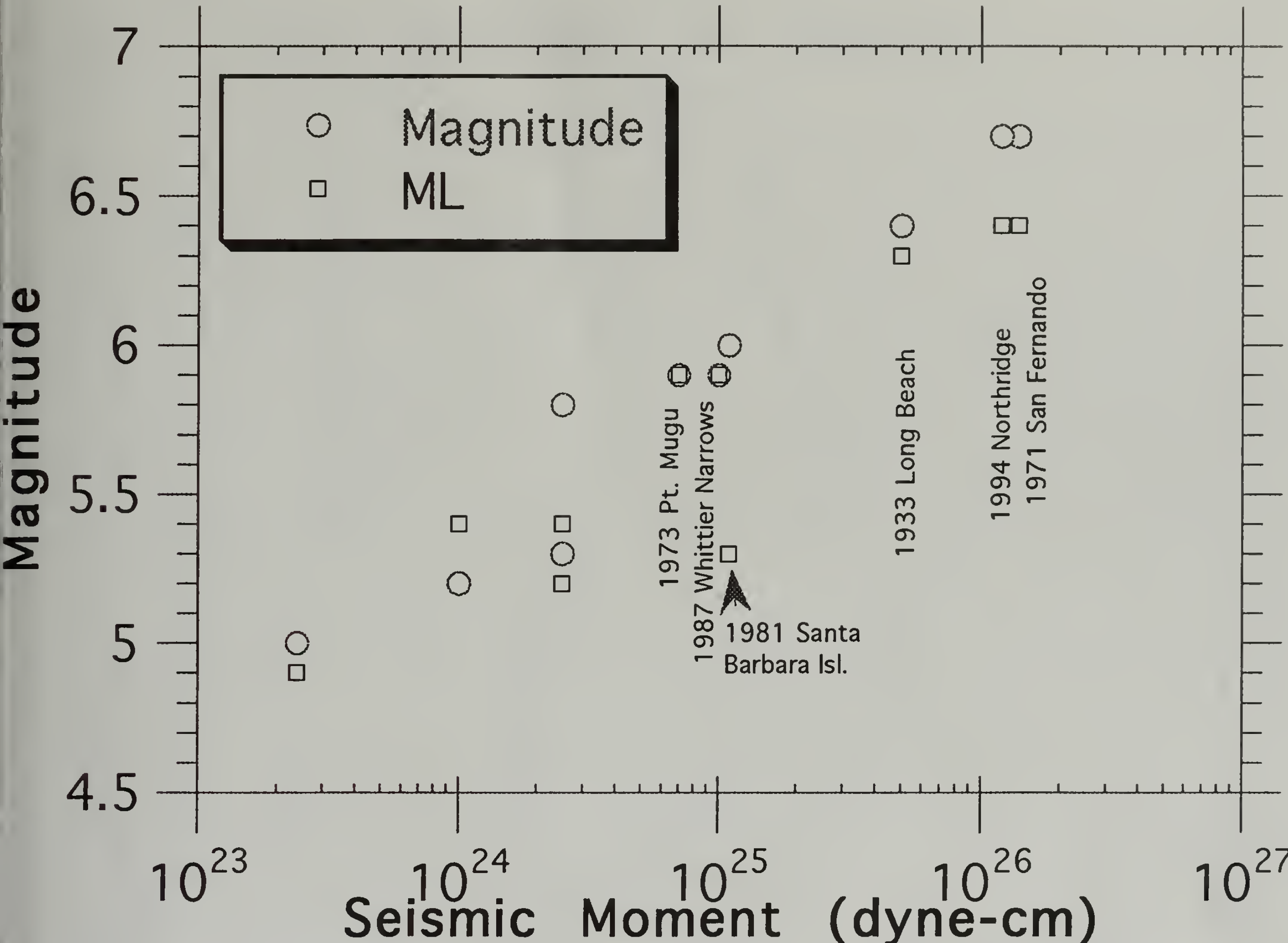


Figure 4. Preferred magnitude and local Richter magnitude (M_L) plotted as a function of seismic moment for earthquakes listed in Table 1.

Depth of Faulting

The overall depth of faulting is important because the maximum size of an earthquake that a fault can produce depends on the fault width. In addition, the distribution of damage depends on whether the fault rupture is shallow or deep. In Table 1 the focal depth of the mainshocks are listed with best estimates of uncertainty in the depth. In Figure 5 the hypocenter and depth distribution of aftershocks is plotted for events with well-known aftershock distributions.

The four deepest events are the 1973 Point Mugu, 1987 Whittier Narrows, 1988 Pasadena, and 1994 Northridge earthquakes. The only earthquake that ruptured the surface is the 1971 San Fernando earthquake which had surface offsets of 1.5-2.3 m (Proctor and others, 1972). The 1987 Whittier Narrows and 1994 Northridge earthquakes are the most obvious cases of events occurring on concealed thrust ramps.

DATA AND PROCEDURES

The P and S arrival times and P wave first-motion data from the Southern California Seismic Network (SCSN), operated by the U.S. Geological Survey and the California Institute of Technology (USGS/CIT), were analyzed to obtain high-quality hypocenters and focal mechanisms. During January - July 1994 the SCSN recorded approximately 8,000 Northridge aftershocks.

Hauksson and others (1995) inverted simultaneous arrival time data from 300 earthquakes for improved hypocenters, a one-dimensional velocity model, and a set of station delays using the VELEST code (Roecker and Ellsworth, 1978). Arrival time data were used from the stations shown in Figure 6. The starting and final velocity models are by Hauksson and others (1995). The resultant models and delays were used as input to HYPOINVERSE (Klein, 1985) to obtain final locations for both sequences, which included more than 10,000 events

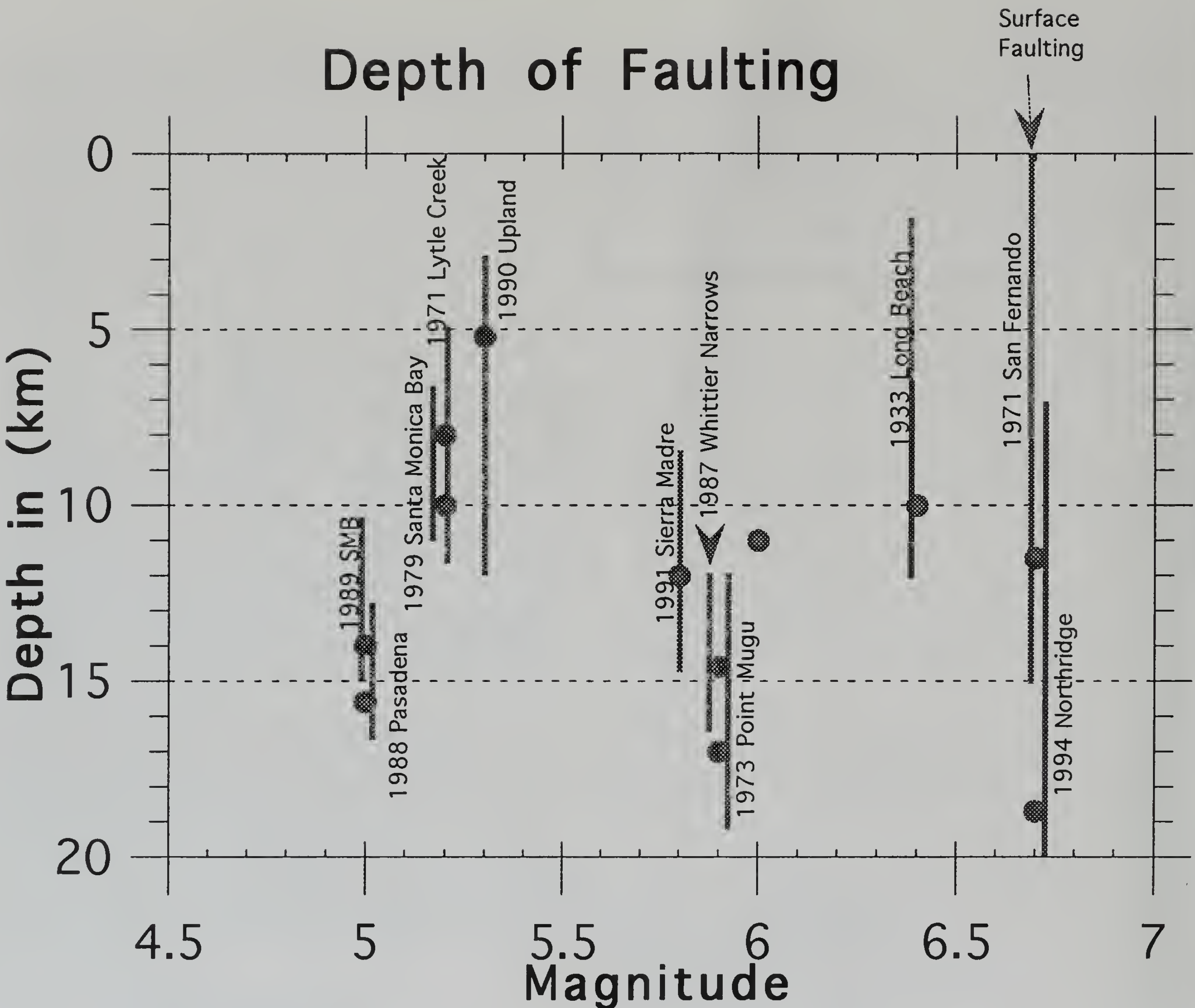


Figure 5. Depth of faulting determined from aftershock distribution for moderate-sized earthquakes in the Los Angeles basin. The hypocenter of each mainshock is indicated with a solid circle.

in 1994 and 1,100 events in 1971-1972. The relative vertical and horizontal uncertainties in the hypocenters are in most cases less than 1 km. The final locations on the average had a root-mean-square residual (rms) of 0.10 s as compared with the rms of 0.25 s when using the starting model.

Single-event, lower hemisphere focal mechanisms were determined using the grid-searching algorithm and computer programs by Reasenberg and Oppenheimer (1985) . The uncertainties in the strike, dip, and rake of the focal mechanisms for the whole data set are 12°, 14°, and 20°, respectively. Focal mechanisms with first-motion polarities for M 4 events are shown in Figure 7 and listed in Table 2.

RESULTS

Precursory Seismicity Clusters?

The epicentral area of the Northridge earthquake remained seismically quiescent during the preceding month. Two different clusters of small earthquakes occurred at distances of 20-25 km during the preceding month (Figure 8). The first occurred under Santa Monica Bay adjacent to the coastline. The second occurred in Santa Clarita Valley, 4 km north of the surface trace of the Holser Fault. Both the spatial and temporal relationships to the subsequent Northridge mainshock suggest but do not require a causative relationship.

Figure 6. Map of the Southern California Seismographic Network (SCSN) showing seismic stations used to relocate the Northridge earthquakes. Seismic stations are shown by solid circles. The M_w 6.7 Northridge mainshock is shown as a diamond.

TABLE 2. Locations and focal mechanisms of earthquakes in the 1994 Northridge sequence.

Origin Date	Time, UT	Latitude N	Longitude W	Depth, km	Mag M_L	Focal Mechanisms[1] Ddir[1]	Dip[1]	Rake	Number of First Motions
Jan. 17, 1994	1230	34° 12.55'	118° 32.44'	18.7	6.7	195°	35°	100°	135
Jan. 17, 1994	1231	34° 15.49'	118° 28.41'	5.4	5.9				
Jan. 17, 1994	1234	34° 16.49'	118° 28.10'	8.5	4.4				
Jan. 17, 1994	1239	34° 15.20'	118° 32.29'	14.0	4.9	220°	30°	110°	71
Jan. 17, 1994	1240	34° 18.36'	118° 30.30'	5.7	4.8				
Jan. 17, 1994	1240	34° 19.95'	118° 35.41'	1.7	5.2				
Jan. 17, 1994	1254	34° 18.22'	118° 27.85'	4.2	4.0				
Jan. 17, 1994	1255	34° 15.82'	118° 34.97'	15.8	4.1	135°	75°	30°	66
Jan. 17, 1994	1306	34° 15.03'	118° 32.95'	9.1	4.6	150°	45°	40°	59
Jan. 17, 1994	1326	34° 18.80'	118° 27.00'	6.1	4.7	165°	45°	-90°	45
Jan. 17, 1994	1328	34° 16.14'	118° 34.56'	0.4	4.0				
Jan. 17, 1994	1356	34° 17.04'	118° 37.53'	19.6	4.4	115°	90°	0°	91
Jan. 17, 1994	1414	34° 19.11'	118° 27.04'	2.6	4.5	60°	90°	170°	60
Jan. 17, 1994	157	34° 17.83'	118° 28.65'	9.3	4.2	230°	85°	130°	97
Jan. 17, 1994	157	34° 17.83'	118° 28.36'	5.7	4.1	210°	70°	-110°	18
Jan. 17, 1994	1554	34° 22.17'	118° 37.86'	13.3	4.8	160°	75°	80°	103
Jan. 17, 1994	1756	34° 13.31'	118° 34.44'	19.7	4.6	225°	50°	120°	130
Jan. 17, 1994	1935	34° 18.27'	118° 27.90'	8.7	4.0	265°	75°	100°	51
Jan. 17, 1994	1943	34° 21.87'	118° 38.56'	13.8	4.1	230°	75°	100°	78
Jan. 17, 1994	2046	34° 17.82'	118° 34.25'	10.1	4.9	160°	80°	40°	129
Jan. 17, 1994	2333	34° 19.42'	118° 42.18'	11.1	5.6	190°	45°	70°	115
Jan. 17, 1994	2349	34° 20.29'	118° 40.18'	9.0	4.0	165°	90°	100°	82
Jan. 18, 1994	039	34° 22.42'	118° 34.08'	6.9	4.4	210°	70°	110°	90
Jan. 18, 1994	040	34° 23.05'	118° 32.73'	4.5	4.2				
Jan. 18, 1994	043	34° 22.22'	118° 42.41'	12.9	5.2	190°	60°	90°	132
Jan. 18, 1994	041	34° 20.83'	118° 37.95'	0.3	4.3	165°	55°	30°	68
Jan. 18, 1994	0723	34° 19.58'	118° 37.92'	15.8	4.0	185°	80°	80°	117
Jan. 18, 1994	1135	34° 12.72'	118° 36.35'	12.7	4.2	80°	75°	90°	70
Jan. 18, 1994	1324	34° 18.48'	118° 34.25'	1.3	4.3	155°	70°	20°	84
Jan. 18, 1994	152	34° 22.36'	118° 33.95'	9.1	4.8	210°	55°	100°	119
Jan. 18, 1994	1551	34° 14.54'	118° 28.31'	12.7	4.0	220°	60°	110°	97
Jan. 19, 1994	440	34° 21.49'	118° 34.14'	3.0	4.3	5°	80°	30°	124
Jan. 19, 1994	443	34° 21.60'	118° 42.62'	14.1	4.0	215°	65°	120°	98
Jan. 19, 1994	714	34° 16.82'	118° 28.44'	11.6	4.0	185°	55°	90°	118
Jan. 19, 1994	913	34° 18.04'	118° 44.45'	15.1	4.1	240°	75°	120°	106
Jan. 19, 1994	014	34° 12.52'	118° 31.12'	18.9	4.5	65°	60°	80°	122
Jan. 19, 1994	1446	34° 17.45'	118° 27.83'	7.2	4.0	220°	65°	100°	87
Jan. 19, 1994	219	34° 21.81'	118° 42.81'	14.3	5.1	210°	70°	110°	124
Jan. 19, 1994	2111	34° 22.37'	118° 37.16'	11.1	5.1	210°	55°	90°	71
Jan. 21, 1994	1839	34° 17.79'	118° 28.14'	10.6	4.5	225°	55°	70°	131
Jan. 21, 1994	1839	34° 17.84'	118° 28.08'	10.4	4.0				
Jan. 21, 1994	1842	34° 18.53'	118° 28.18'	7.9	4.2	205°	55°	80°	5 4
Jan. 21, 1994	1852	34° 18.05'	118° 27.36'	8.9	4.3	190°	40°	60°	104
Jan. 21, 1994	1853	34° 17.81'	118° 27.20'	7.1	4.4	215°	45°	90°	5 3
Jan. 23, 1994	855	34° 17.65'	118° 26.01'	9.7	4.1	235°	45°	120°	116
Jan. 24, 1994	415	34° 20.62'	118° 33.44'	8.9	4.6	200°	55°	110°	140
Jan. 24, 1994	550	34° 21.43'	118° 37.97'	12.0	4.3	180°	70°	60°	126
Jan. 24, 1994	554	34° 21.73'	118° 38.00'	10.9	4.2	180°	65°	70°	107
Jan. 27, 1994	1719	34° 16.32'	118° 34.16'	16.3	4.6	230°	10°	110°	132
Jan. 28, 1994	209	34° 22.22'	118° 30.13'	4.0	4.2	215°	35°	100°	62
Jan. 29, 1994	1120	34° 18.32'	118° 34.62'	1.6	5.1	330°	80°	-20°	124
Jan. 29, 1994	1216	34° 16.75'	118° 36.62'	3.6	4.3	140°	80°	30°	102
Feb. 6, 1994	1319	34° 17.15'	118° 29.04'	11.9	4.1	260°	10°	-5 0°	136
Feb. 25 1994	1259	34° 21.25'	118° 29.19'	3.7	4.0	155°	60°	-80°	119
Mar. 20, 1994	2120	34° 13.57'	118° 28.90'	14.7	5.2	185°	50°	60°	158
May 25, 1994	1256	34° 18.07'	118° 23.95'	11.6	4.4	170°	60°	70°	134
Jun. 15, 1994	559	34° 18.11'	118° 24.11'	11.2	4.1	220°	45°	90°	90

[1] Ddir – dip direction of the nodal plane; Dip – dip of the nodal plane.

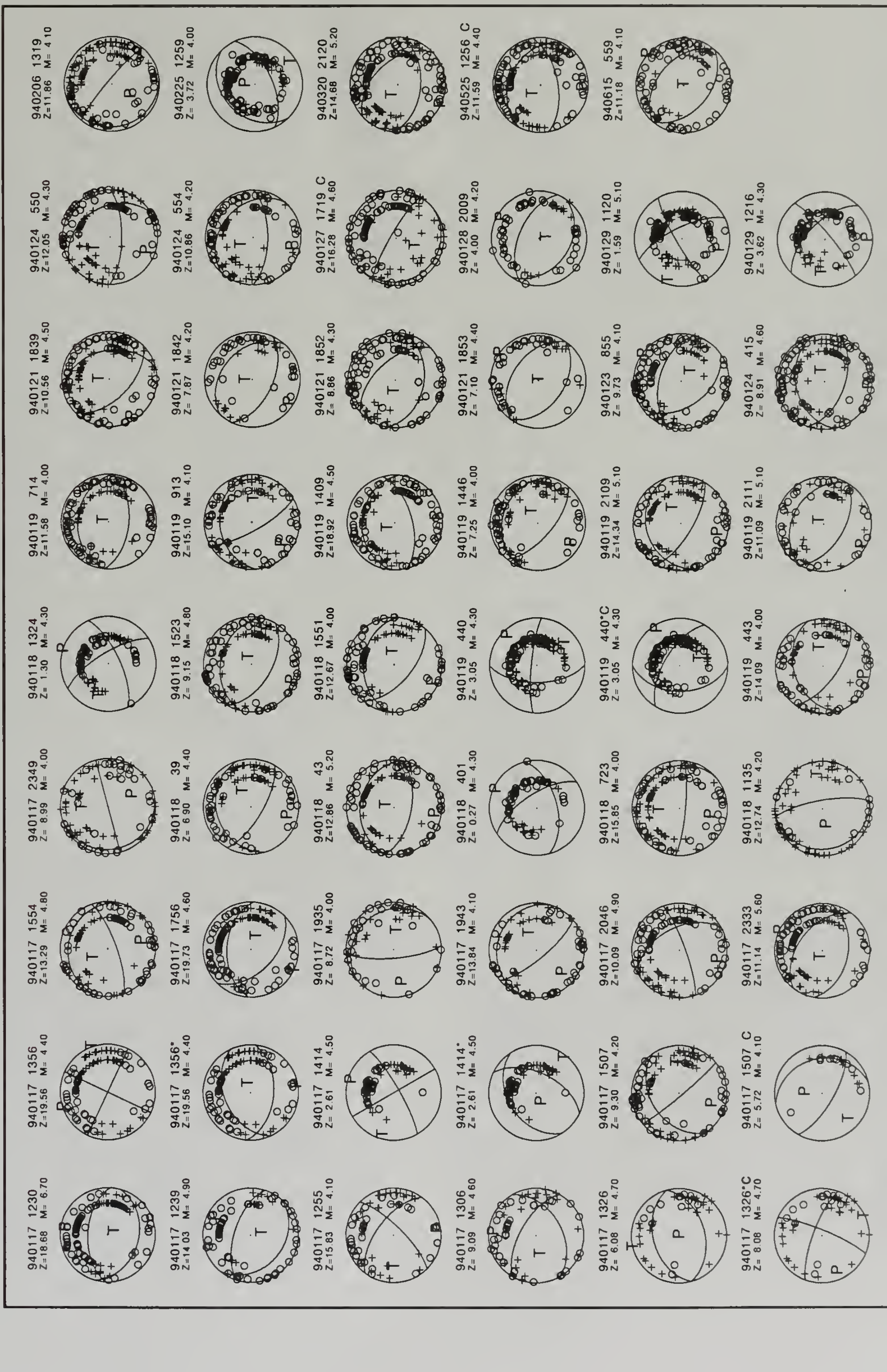


Figure 7. Single-event, first motion lower-hemisphere focal mechanisms of M 4.0 events. Compressional first motions are shown by pluses and dilational first motions are shown by open circles. Duplicate focal mechanisms are flagged by a star.

The Santa Monica swarm during the week before January 17, 1994 was located 25 km due south of the mainshock epicenter. The swarm started with an M3.7 mainshock on January 9th at 2300 UT (Universal Time). This shock was felt in west Los Angeles although it caused no significant damage. During the next seven days a total of 15 events of M 1.5 were recorded with the largest aftershock being a M3.5 on January 12th (1928 UT). This sequence is referred to as a swarm because the two largest events were of similar size, and because the rate of earthquake activity stayed about the same for 2 or 3 days, rather than decaying with time as aftershocks normally do.

The Santa Monica swarm formed a tight cluster of less than 1 km radius in the depth range of 3-12 km. This depth distribution is significantly shallower than the depth of the Northridge sequence (Figure 8C). The locations and focal mechanisms of these 15 events show that this swarm occurred on a previously unmapped offshore reverse fault, with a nearly east-west strike and possibly a steep dip to the south. This sequence is a part of the north-south contractional deformation of the Transverse Ranges. The last event in the Santa Monica swarm occurred about 18 hours before the Northridge mainshock.

During the 16 hours preceding the mainshock, a small cluster of four earthquakes of M1.3-1.9 occurred at 15 km depth, located 35 km north-northwest of the future mainshock epicenter. The largest of these events had a thrust focal mechanism with one east-striking nodal plane dipping gently to the north. Because these events are of small magnitude and occurred at depths of 15 km, it is not possible to assign them to surficial faults. These events, tightly clustered within a volume of 1 km^3, and the focal mechanisms are consistent with the ongoing contractional deformation of the Transverse Ranges (Figure 8).

Both the Santa Monica and the Holser swarm are unusual and their relationship to the Northridge mainshock is not understood. Swarms like the Santa Monica swarm are fairly rare along the Santa Monica coastline although they are common further offshore in Santa Monica Bay (Hauksson and Saldivar, 1989). Small clusters like the Holser swarm, however, have occurred in this region in the past (Figure 2). Because both clusters occurred on different faults and more than one fault dimension away from the subsequent Northridge mainshock, we do not consider either cluster to be a precursor or a foreshock sequence to the Northridge mainshock, as defined by Jones (1984) .

FOCAL MECHANISMS OF THE MAINSHOCK AND M 4 AFTERSHOCKS

The first motion focal mechanism of the mainshock exhibited one nodal plane striking N75°±10°W and dipping 35°±5° south-southwest with a rake of 100°±10° (Hauksson and others, 1995). Other determinations of the mainshock focal mechanism based on teleseismic and regional broad-band waveforms show a more northerly strike of N50-60°W and a somewhat steeper dip of 40-45° to the south-southwest (Dreger, 1994; Thio and Kanamori, 1995). This difference in the mainshock focal mechanism determined with different frequency waves suggests a small increase in dip along strike and possibly a curved rupture surface. Such an increase in dip along strike can also be seen in the distribution of aftershocks.

Although no surface rupture has been found (Scientists of USGS and SCEC, 1994), several preliminary interpretations of the mainshock faulting have been offered. One interpretation suggests that the Oak Ridge Fault, mapped to the west in the Ventura basin, extends into this region (Yeats and Huftile, 1995). Another interpretation could be that some of the surficial faults exposed farther north, such as the Holser Fault, are responsible for the earthquake. A third interpretation models the earthquake as slip on a south-dipping thrust ramp beneath the San Fernando Valley (Davis and Namson, 1994). The seismological evidence for the mainshock faulting, the focal mechanism, and the spatial distribution of aftershocks are consistent with all three interpretations.

The large aftershocks occurred both to the north and south of the surface trace of the east-west-striking, north-dipping Santa Susana thrust fault, the most prominent surficial reverse fault in the region. Although it did not rupture in the mainshock, it appears to influence the spatial distribution of aftershocks. It has two lateral ramps, defining lateral separation of the surface trace of the fault, the San Fernando lateral ramp (SFLR) on the east side, and the Gillibrand Canyon lateral ramp (GCLR) on the west side (Yeats, 1987) (Figure 9). Analysis of drill hole data indicates that the Santa Susana Fault has a convex shape and a low dip near the surface (Yeats, 1987).

The available focal mechanisms of 57 aftershocks of M_L 4.0 and of the mainshock are shown in Figure 9 and listed in Table 2. Nearly all of these focal mechanisms showed thrust faulting with only a few strike-slip and normal faulting events. The largest aftershock of M_L5.9

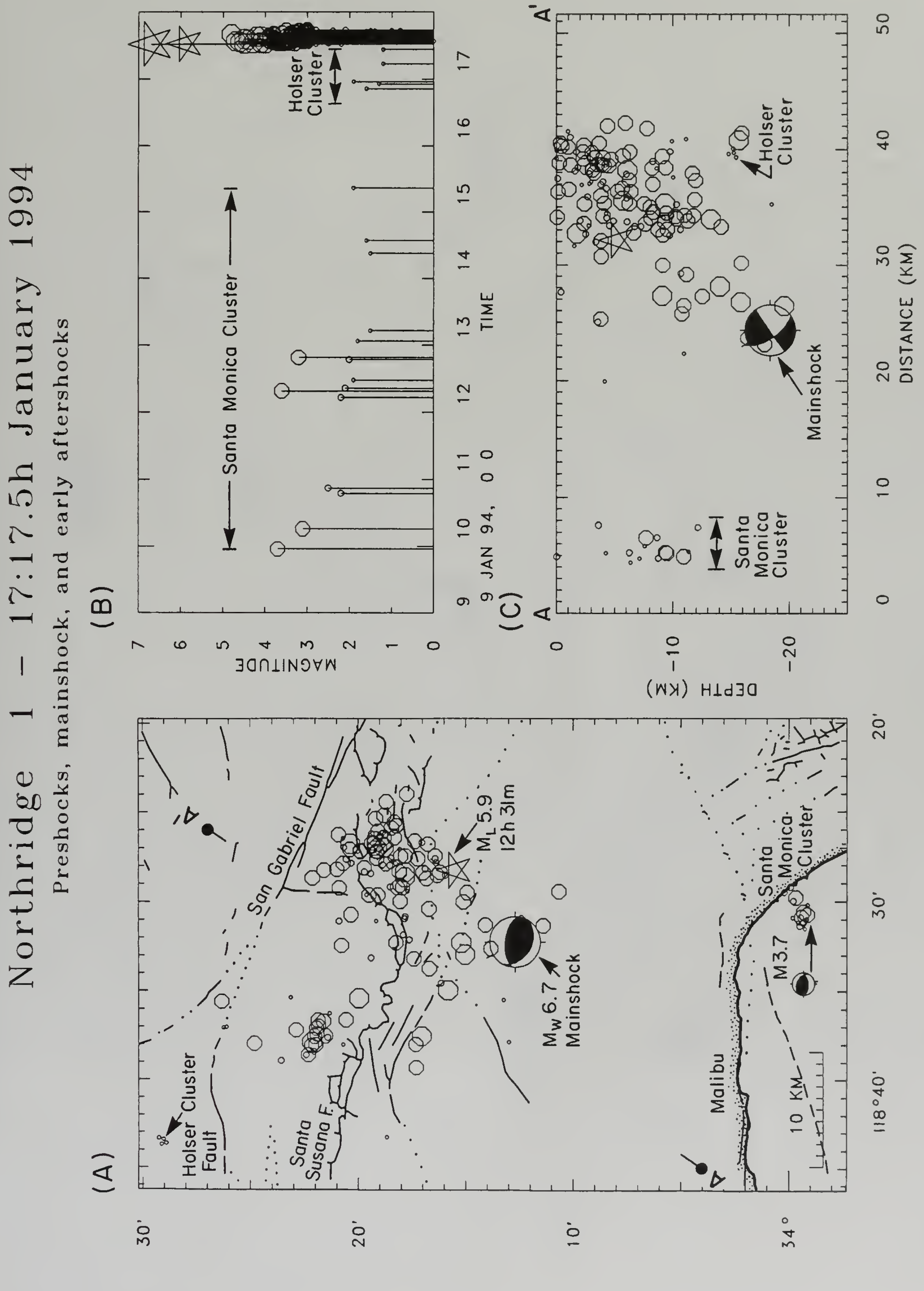


Figure 8. The Northridge mainshock and the two clusters of preshocks located in Santa Monica and near the Holser Fault. (A)Map of the preshocks, mainshock, and first 8 hours of aftershock activity. Mainshock is represented by its focal mechanism. (B)Magnitude versus time for the preshocks, mainshock, and early aftershocks. (C)Depth cross section of the preshocks, mainshock, and early aftershocks.

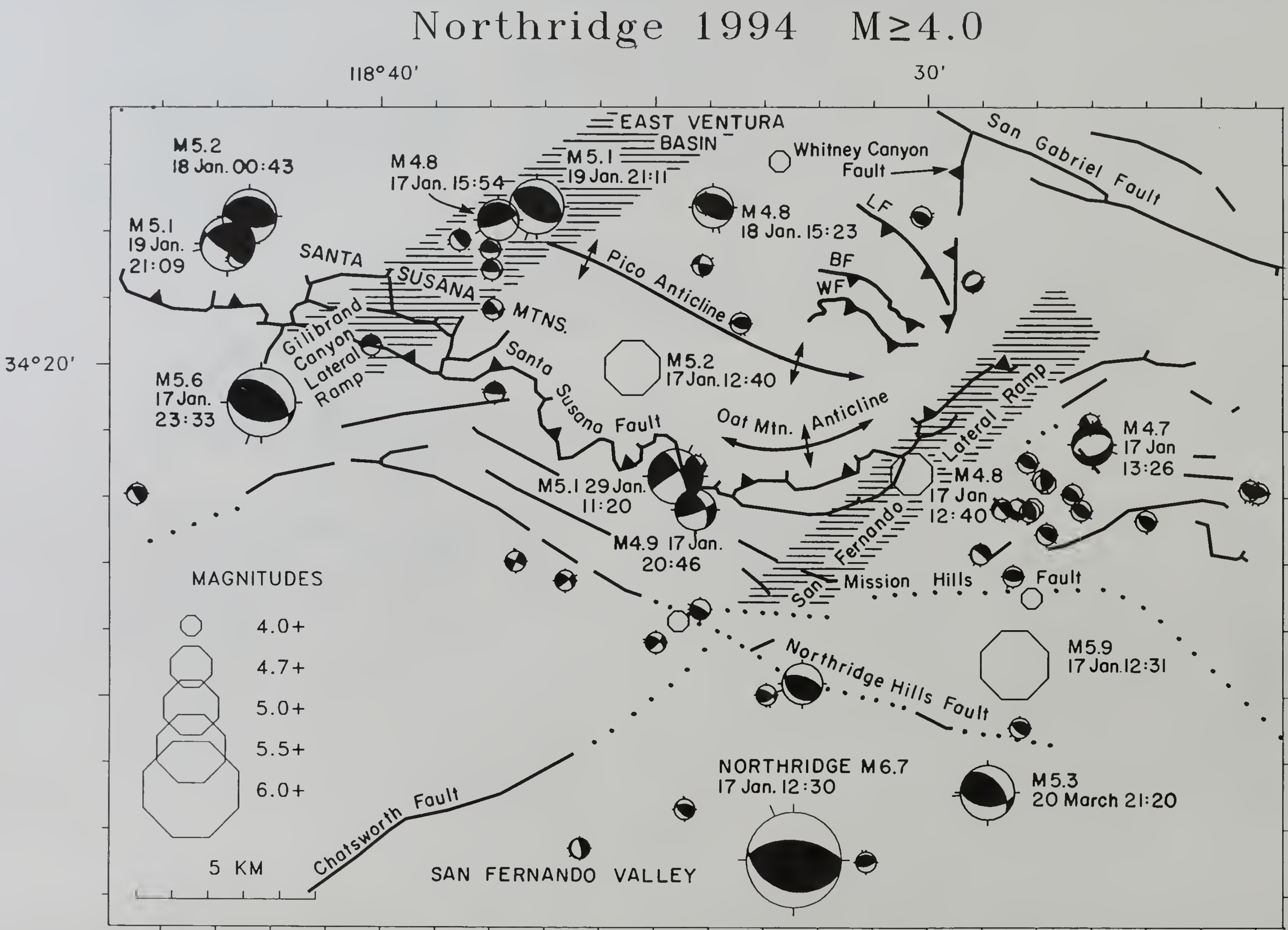


Figure 9. Northridge aftershock region showing lower-hemisphere, first-motion focal mechanisms of M 4 earthquakes recorded by the SCSN from January through September 1994, and major faults (dotted where inferred) from Jennings (1975) . Because the M5.9 aftershock occurred too closely in time to the Northridge mainshock or, in several cases, aftershocks were preceded by immediate foreshocks, their focal mechanism could not be determined.

followed the mainshock within a minute and was located 10 km to the east-northeast of the mainshock. No focal mechanism is available for this event. The second largest aftershock of M_L5.6 occurred 11 hours later and was located about 20 km to the northwest of the mainshock. This aftershock had a thrust-faulting focal mechanism similar to the mainshock. This and two other thrust-faulting aftershocks of $M>5$ located near the trace of the Santa Susana Fault could be associated with either south- or north-dipping fault structures.

A cluster of M_L 4.0 aftershocks was located along the eastern margin of the mainshock rupture plane, about 5 km to the east of the San Fernando lateral ramp. The San Fernando lateral ramp is a 5 km-long left step in the Santa Susana thrust fault (Yeats, 1987). This cluster is bounded on the north side by the surface trace of the Santa Susana Fault and includes mostly events with thrust mechanisms. However, the largest normal faulting event (M_L4.7) was located in this cluster.

Another cluster, forming the northwest side of the aftershock zone, also is comprised of mostly events with thrust mechanisms. Several of the larger events of this cluster are located within the Gillibrand Canyon lateral ramp, as defined by Yeats (1987), near the northwest end of the Pico anticline. To the west of the Gillibrand Canyon lateral ramp the Santa Susana Fault steps left and steepens in dip (Yeats,1987). A possible tectonic association between these events and adjacent geological features such as the Pico anticline and the Gillibrand Canyon lateral ramp, however, remains unresolved.

Strike-slip deformation has occurred during the late Quaternary along faults such as the Northridge Hills Fault and the Mission Hills Fault. Three of strike-slip faulting M 4 aftershocks are located near the surface trace of the Northridge Hills Fault. No large aftershocks were located near the Mission Hills Fault, even though significant ground deformation in this region was caused by the Northridge mainshock (Scientists of USGS and SCEC, 1994). Only one of the eight $M_L>5.0$ aftershocks showed a strike-slip focal mechanism, and was located between the surface traces of the Northridge Hills and the Santa Susana faults. Most of the strike-slip and normal faulting aftershocks occurred at shallow depth above the main rupture surface where strike-slip or extensional deformation of the hanging wall may be expected.

SPATIAL DISTRIBUTION OF AFTERSHOCKS

The 1994 Northridge earthquake and the more than 8,000 aftershocks that occurred from January 17 to July 31, 1994 form a complex spatial distribution. In map view the aftershocks form a 45 km-long and 40 km-wide zone (Figure 10). The mainshock rupture as determined from waveform data (Wald and Heaton, 1994), started at the southeastern corner of this zone and extended about 15 km west-northwest from the mainshock epicenter and about 20 km up a 35-42° dipping surface to the north-northeast, covering less than one third of the aftershock zone.

Three cross sections extend from south-southwest to north-northeast (Figure 11). The cross section C-C' shows aftershocks that occurred along the eastern edge of the mainshock rupture surface. These hypocenters form a south-southwest-dipping distribution in the depth range of 5-15 km with a small number of aftershocks extending down to 20 km depth. The lower depth bound to the densest part of the aftershock distribution appears to coincide with the steeply dipping Northridge Hills Fault. Most of the shallow aftershocks were located near the surface trace of the Santa Susana and Verdugo faults.

The cross section B-B' includes the hypocenter of the mainshock and shows the 35-40° dipping zone of aftershocks from 23 km to about 7 km depth, located mostly under the San Fernando Valley. If the 35° south-southwest dipping nodal plane of the mainshock is extended to shallower depths, the rupture surface is located near the lower surface of this dipping aftershock zone. The deep end of this zone is defined by a few aftershocks that extend as deep as 23 km. Above approximately 7 km depth, the aftershock zone is less well expressed as a southwest-dipping tabular feature but is rather a cloud of aftershocks representing diffuse deformation of an overlying anticlinal fold. The San Gabriel Fault limits the northeast spatial extent of most of the shallow aftershocks. The southwestern edge of the distribution of shallow aftershocks is located further to the southwest, above the mainshock rupture surface and reflects the distributed deformation of the hanging wall.

The aftershocks in cross section A-A' occurred west of the mainshock rupture surface. They form a diffuse distribution beneath the Santa Susana Mountains and

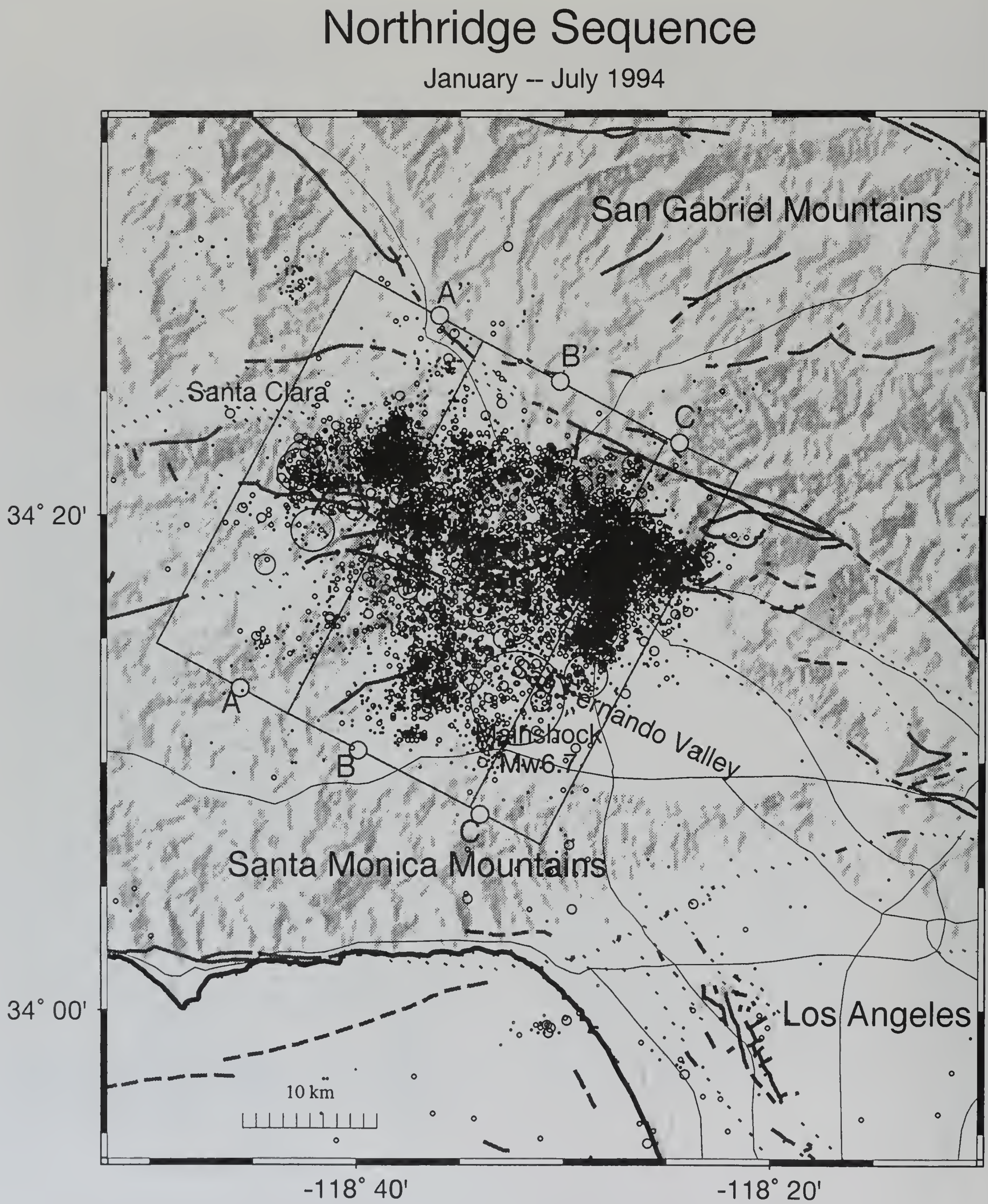


Figure 10. Map of the 1994 Northridge earthquake, its aftershocks, and major late Quaternary faults (dotted where inferred). Symbol size is scaled with magnitude. See Figure 11 for cross sections.

appear to be on different faults that did not rupture in the mainshock. There is some indication in the cross section of a wedge-shaped structure illuminated by both south and north dipping trends of aftershocks in the depth range of 13-18 km. This wedge-shaped structure coincides with the Gillibrand Canyon lateral ramp. The Northridge Hills Fault brackets the distribution to the south while the northern edge of the distribution is midway between the Santa Susana and Holser faults.

In summary, the complex aftershock distribution exhibits several major distinctive features. First, the southwest-dipping zone of aftershocks is consistent with the focal mechanism of the mainshock and finite rupture models of the mainshock. Second, mapped surficial faults appear to bound crustal blocks where most of the aftershocks occurred. Third, the hanging wall deformation appears to indicate some extensional deformation as evidenced by a small component of normal and strike-slip motion in the focal mechanisms.

RELATION TO THE 1971 SAN FERNANDO EARTHQUAKE

Both the M_w6.7 1971 San Fernando and the M_w6.7 1994 Northridge earthquakes contributed to the tectonic process of north-south contraction and uplift of the Transverse Ranges (Figure 12). The hypocenters of the 1971 sequence are determined from phase data from SCSN for 1971 and 1972, and portable instruments, for the time period February to April 1971 (Mori and others, 1994). The 1971 hypocenters were relocated using the new Northridge velocity model. In detail, both sequences have different characteristics in terms of the faulting process and their seismological properties.

The details of the seismicity preceding both sequences differed significantly. The three weeks prior to the Northridge earthquake were marked by the Santa Monica Bay and the Holser clusters. No similar preshocks were observed during the three weeks prior to the 1971 San Fernando earthquake (Ishida and Kanamori, 1978).

The 1971 San Fernando earthquake ruptured a north-northeast dipping fault from 12-15 km depth up to the surface (e.g. Heaton, 1982). The initiation of the depth of faulting in the San Fernando earthquake that was constrained both with waveform modeling (Heaton, 1982) and with arrival time data was 4-8 km shallower than for the Northridge earthquake. Using additional arrival times from strong motion instruments Hadley and Kanamori (1977) obtained an improved hypocentral location of 34°25.45'N and 118°22.63'W at a depth of 11.5 km. The San Fernando aftershocks were distrib-

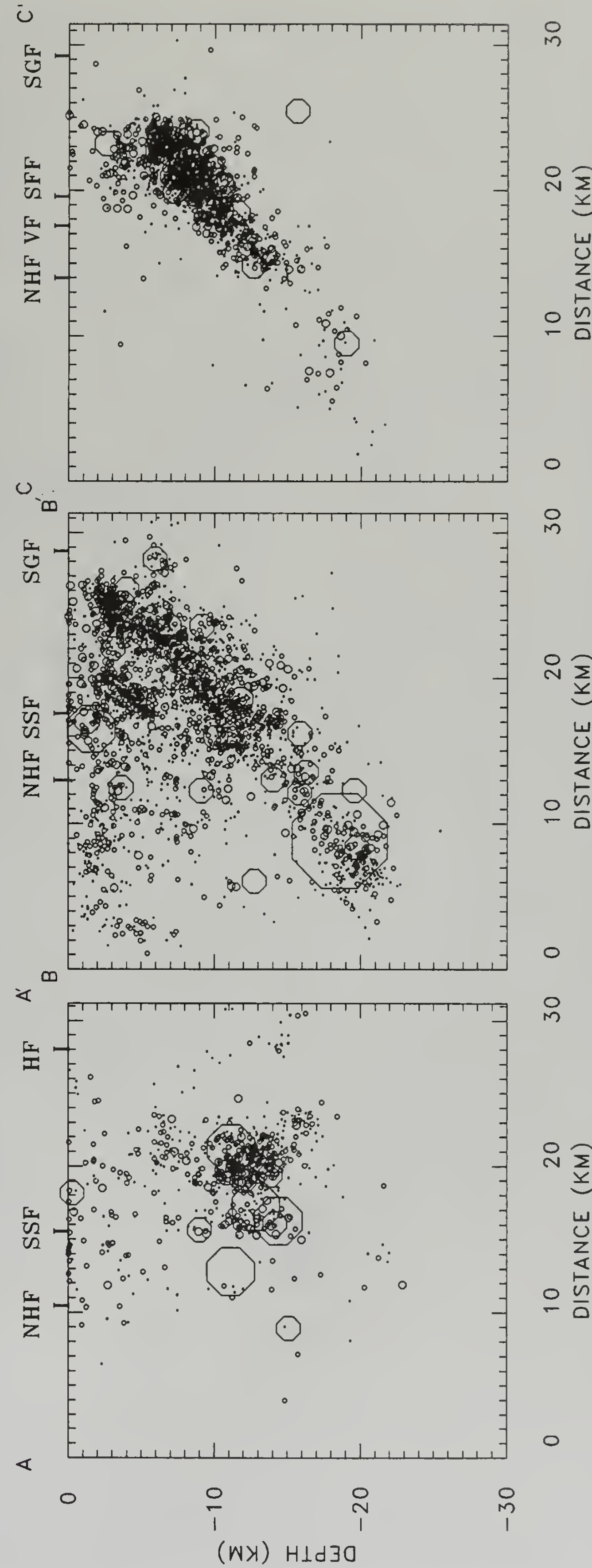
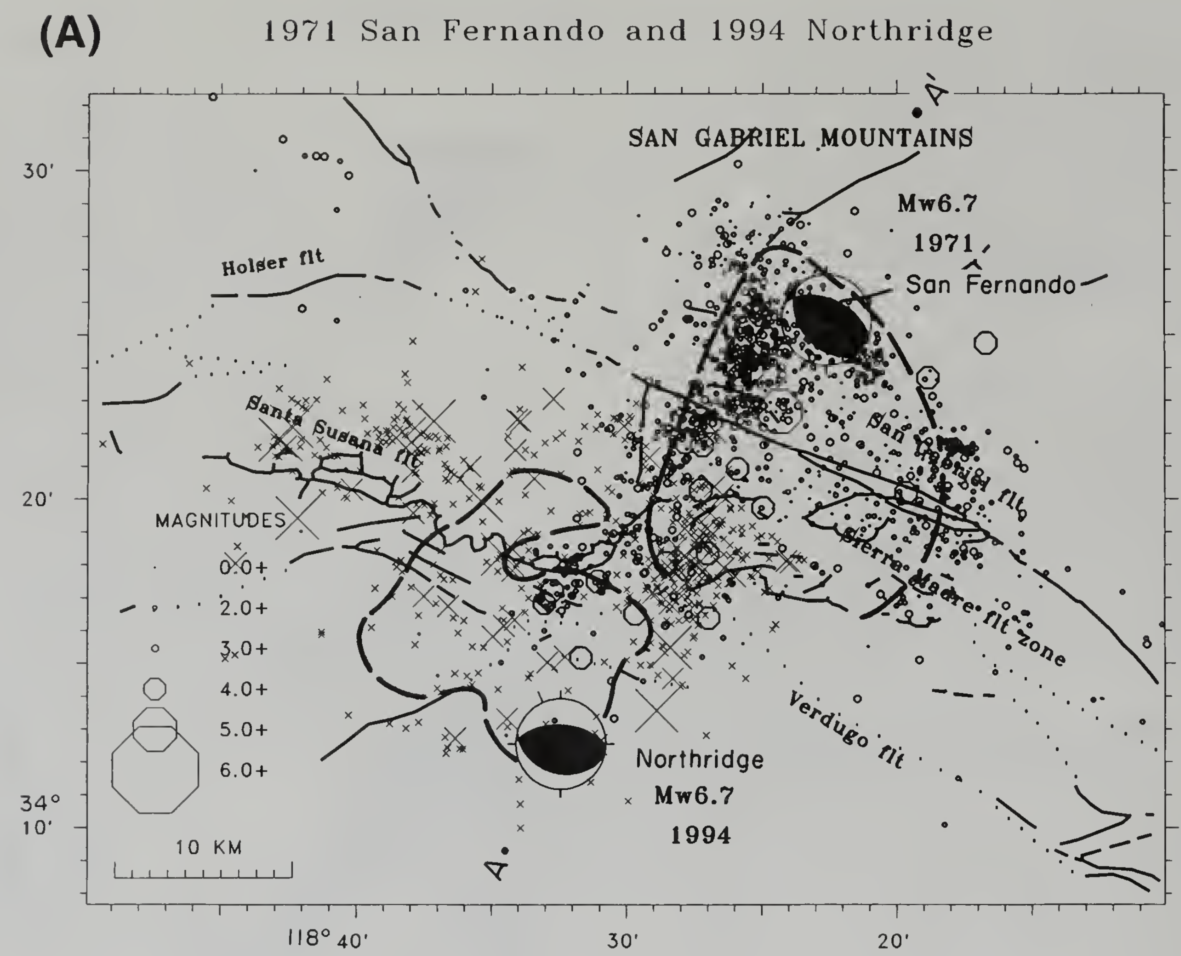


Figure 11. Depth cross sections taken orthogonal to strike, A-A', B-B', and C-C' (see Figure 10 for cross section locations) include all events in each box having horizontal and vertical errors less than 2 km. NHF, Northridge Hills Fault; SSF, Santa Susana Fault; SGF, San Gabriel Fault, HF, Holser Fault; VF, Verdugo Fault; CWF, Chatsworth Fault, and SFF, San Fernando Fault.



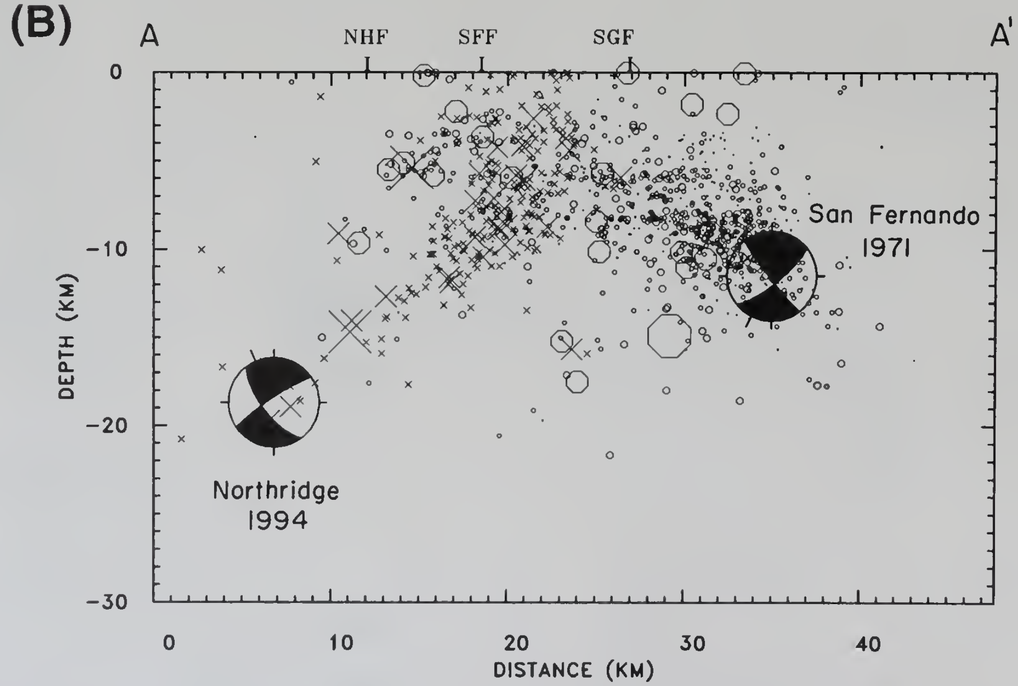


Figure 12. (A) Map and (B) northeast striking cross section (A-A') showing both the 1971 San Fernando (open symbols) and the 1994 Northridge aftershocks (x symbols). Aftershock data is from portable instruments, February to April 1971, (Mori and others, 1994), and SCSN data from 1971 and 1972. Approximate rupture surfaces for the 1971 (Heaton, 1982) and 1994 (Wald and Heaton, 1994) earthquakes are also shown.

uted around the mainshock fault plane, which had a strike of N67°W, dip of 52°, and rake of 72° based on the first motion focal mechanism (Whitcomb and others, 1973). In addition, Whitcomb and others (1973) used aftershock hypocenters and focal mechanisms to identify a west-side-down step in the mainshock rupture plane along a northeast trending tear (the Chatsworth trend). In contrast, the Northridge rupture started at 19 km, terminated at 8 km, and no strike-slip tear faulting is apparent.

The 1994 Northridge M_L 4.0 aftershocks were located near the edges of the aftershock zone and mostly exhibited thrust focal mechanisms. This is in contrast to the large aftershocks of the 1971 M_W6.7 San Fernando earthquake that had a variety of mechanisms at the edge of the mainshock rupture as well as a trend of left-lateral strike-slip deformation extending to the south-southwest toward the Chatsworth Fault (Whitcomb and others, 1973) .

The 1971 San Fernando and the 1994 Northridge earthquakes ruptured partially abutting fault surfaces on opposite sides of a ridge (Mori and others, 1995). The Northridge rupture was deeper and possibly bounded on the up-dip side by the north-northeast dipping fault systems that ruptured in 1971. The epicenters of the 1971 San Fernando and 1994 Northridge earthquakes are located about 26 km apart along a northwest trending line (Figure 12). The actual rupture surfaces do not cross cut each other. Although their aftershock zones abut, they do not overlap in any significant way, suggesting that none of the faults activated in 1971 were reactivated in 1994. Even though the Chatsworth trend extends into the Northridge aftershock zone, it is confined within the hanging wall, above the mainshock rupture surface and the deeper distribution of 1994 aftershocks.

AFTERSHOCK STATISTICS

Although the Northridge aftershock sequence is dying off slightly more quickly than average, it is also more active than most California aftershock sequences. For comparison, the 1971 San Fernando sequence was smaller than average and the 1933 Long Beach sequence was even more energetic than Northridge (Scientists of USGS and SCEC, 1994).

Because the decay of the Northridge sequence is rapid, the number of aftershocks expected in 1995 is small compared to the total sequence. We expect only 18 earthquakes of M 3 and two of M 4 in 1995. The probability of an aftershock of M 5 in 1995 is only 25%.

DISCUSSION

In several respects, the Northridge earthquake was a surprise. It occurred on a deep blind south-southwest dipping thrust ramp beneath the San Fernando Valley, it was not obviously associated with any surficial geological features such as Quaternary folds, and its location was close to the location of the 1971 San Fernando earthquake. Despite these unexpected aspects however, earthquake activity was anticipated because the seismicity rate in the Los Angeles area has been anomalously high in the past 25 years (Figure 3). Furthermore, the known earthquake deficit associated with blind or concealed faults strongly suggested that large earthquakes should be expected in the greater Los Angeles region (Hauksson, 1992).

Surficial Geological Signature of the Ramp

Unlike previous earthquakes on blind thrust faults in California, the Northridge earthquake is not obviously associated with any surficial geological structures. No surface faulting was observed because fault rupture terminated at a depth of 7 km. The uplift associated with the mainshock was centered at the northern edge of the San Fernando Valley (Hudnut and others, 1994) and did not coincide directly with a Quaternary anticline or another type of a topographic high. Although the Pico anticline fortuitously has the same strike as the mainshock fault plane, the fold is located 8 km to the north of the region of maximum uplift (Hudnut and others, 1994) .

The Oak Ridge Fault, a south-dipping reverse fault in the central and western Transverse Ranges with a slip rate of approximately 5 mm/yr, may affect the tectonics of the epicentral area (Yeats, 1988; Yeats and Hufltile, 1995) . The Oak Ridge Fault has been mapped along the southern edge of the Ventura basin, from the Santa Barbara channel to the western end of the Santa Susana Fault, and it defines the southern edge of the Santa Clara Valley. Further east, the Oak Ridge Fault may extend beneath the Santa Susana Fault, and thus its interaction with the Santa Susana Fault and its role in the active tectonics of the epicentral region are ambiguous.

The common assumption that all large California earthquakes are associated with obvious surficial geological faults or folds (Stein and Yeats, 1989) thus may not apply to the Northridge earthquake. In the case of the Northridge earthquake, the cumulative slip on the thrust ramp may be so small that a perceptible fold has not yet formed. Alternatively, the movement on other geological structures may be more rapid and may complicate the surficial expression on this new fold.

Sub-Horizontal Detachment?

Previously identified north-dipping reverse faults such as the Santa Susana and Sierra Madre faults at the base of the east-west trending mountains are the principal structures responsible for generating uplift and the local high topography (Dibblee, 1982). The mountains are also uplifted by concealed north-dipping thrust ramps, such as the thrust ramp beneath the Santa Monica Mountains, which also had been previously identified (Namson and Davis, 1992). Movement on the south dipping thrust ramp that caused the Northridge earthquake, deep beneath the middle of the San Fernando Valley, also caused uplift of the mountains and the floor of the San Fernando Valley. The south-dipping thrust ramps probably play a smaller role in the over all deformation of the region than the north dipping structures.

All of these faults have been postulated to root in a sub-horizontal decollement based on both seismological and geological data (Hadley and Kanamori, 1977; Davis and Namson, 1994). The regional seismicity and M 3.5 aftershocks following the 1971 San Fernando earthquake were analyzed by Hadley and Kanamori (1977). Because the two deepest events at focal depth of 12-14 km had focal mechanisms with one sub-horizontal nodal plane, they inferred a sub-horizontal decollement below the San Fernando Valley at depth of about 15 km. Webb and Kanamori (1985) also suggested that a sub-horizontal decollement was present based on a few more mechanisms with one sub-horizontal nodal plane. In some cases the Northridge aftershocks also had sub-horizontal planes in this depth range, consistent with the presence of sub-horizontal faults but only of limited spatial extent.

The 1994 Northridge earthquake was at least 5 km deeper than any of the previous focal mechanisms with sub-horizontal nodal planes. Thus, if there is a regional detachment at the base of these crustal ramps, it must be as deep or deeper than 20 km. Because the Northridge aftershock distribution does not flatten in the depth range of 17-21 km, it provides no evidence for the presence of a sub-horizontal regional detachment. Thus these seismological data to some extent favor the latest tectonic modeling by Yeats (1993) who proposed that crustal thickening, not horizontal detachments, may be the important mechanism for accommodating horizontal compression in the Ventura region. Otherwise, a regional detachment would need significantly more topographic relief than suggested by existing models (Namson and Davis, 1992).

Seismic Hazard

The 1994 Northridge earthquake reemphasized the seismic hazard of blind or concealed faults, which we have recognized more fully since the 1987 Whittier Narrows earthquake (Hauksson and others, 1988). The Northridge earthquake occurred at a greater depth than any previous large earthquake in this region. It began rupturing at 19 km and terminated upwards at a depth of 7 km (Wald and Heaton, 1994). The upper limit of the rupture is similar to what has been reported for some of the previous earthquakes in the region (Figure 4; Hauksson, 1994). This relatively large depth extent of the Northridge earthquake shows that the seismogenic width of faults and thrust ramps in the Los Angeles area may be 5-10 km larger than previously estimated (Ziony and Yerkes, 1985). This large seismogenic width in turn increases the size estimate of maximum possible earthquakes. This means that many fairly short fault segments may rupture in larger earthquakes than previously thought.

The surficial mapping may identify all potential sources of M>7 earthquakes, while some source zones of M<7 earthquakes go undetected. The occurrence of a Northridge-sized earthquake that can radiate damaging ground motions over a large area (Scientists of USGS and SCEC, 1994) thus needs to be included as a random event in seismic hazards calculations.

The relatively close occurrence of the 1994 Northridge earthquake to the 1971 San Fernando earthquake and spatial association of the aftershock sequences was a surprise. Prior to the 1994 event, segments of the Sierra Madre Fault system other than the 1971 San Fernando segment were thought to be more likely to break (Hauksson, 1994). In light of rapid tectonic strain accumulation in the region (Donnellan and others, 1993) and the absence of large earthquakes over the last 200 years (Hauksson, 1992), large earthquakes were expected. Although the 1994 and 1971 events occurred on different fault systems, they both released some of the accumulated north-south contractional tectonic strain in the Transverse Ranges. Stein and others (1994) used dislocation modeling to argue that the 1994 event was triggered by stress loading from the 1971 event. Such a triggering mechanism is possible but not required because ample tectonic strain remains stored on faults in the region.

CONCLUSIONS

There are four main seismological and tectonic lessons from the Northridge earthquake. First, the mainshock hypocenter was relatively deep, suggesting that the seismogenic width of faults in the region may be 5-10 km greater than previously thought. Second, the Northridge earthquake and its aftershocks do not correlate easily with any mapped surficial geological faults or folds, although some of the deformation may be controlled by northeast trending lateral ramps. Potential earthquake sources of M<7 thus may be routinely missed in geologi-

cal investigations of the region. Third, the strain released in the 1994 earthquake was not sufficient to significantly decrease the accumulated strain in the region. Because no other major (M>7) earthquakes have occurred in the region for at least 200 years, or possibly longer, significant accumulated strain remains to be released on surficial or concealed faults in the region. Fourth, the relative uniformity of thrust focal mechanisms indicated that the stress release in the mainshock was not complete. Alternatively, slip partitioning plays an important role in the deformation of this region and future large earthquakes can have a significant strike-slip component.

ACKNOWLEDGMENTS

We are grateful to the seismic analysts of Caltech and the USGS for quick and competent processing of the earthquake data. This research was partially supported by USGS grant 1434-94-G-2440, USGS cooperative agreement 1434-92-A-0960, and NSF grant 94-16119 to Caltech. Southern California Earthquake Center publication 180. Contribution 5483, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena.

REFERENCES

Aki, K., and Richards, P.G., 1980, Quantitative seismology, Theory and methods: W. H. Freeman and Co., New York, 932 p.

Bent, A.L., 1990, Source characteristics of recent and historic earthquakes in central and southern California, Results from forward, modeling: California Institute of Technology, Ph.D. Thesis, 149 p.

Bent, A.L., and Helmberger, D.V., 1991, Seismic characteristics of earthquakes along the offshore extension of the Western Transverse Ranges: Seismological Society of America Bulletin, v. 81, p. 399-422.

Çemen, I., 1989, Near-surface expression of the eastern part of the San Cayetano Fault – A potentially active thrust fault in the California Transverse Ranges: Journal of Geophysical Research, v. 94, p. 9665-9677.

Corbett, E.J., 1984, Seismicity and crustal structure studies of southern California – Tectonic implications from improved earthquake locations: California Institute of Technology, Ph. D. Thesis, 231 p.

Crook, R., Jr., Allen, C.R., Kamb, B., Payne, C.M., and Proctor, R.J., 1987, Quaternary geology and seismic hazard of the Sierra Madre and associated faults, western San Gabriel Mountains *in* Morton, D.M. and Yerkes, R.F., eds., Recent Reverse Faulting in the Transverse Ranges, California: U. S. Geological Survey Professional Paper 1339, p. 27-64.

Davis, T.L., and Namson, J.S., 1994, A balanced cross section analysis of the 1994 Northridge earthquake and thrust fault seismic hazards in southern California: Nature, v. 367, p. 167-169.

Dibblee Jr., T.W., 1982, Geology of the Santa Monica Mountains and Simi Hills, southern California *in* Fife, D.L. and Minch, J.A., eds., Geology and Mineral Wealth of the California Transverse Ranges: South Coast Geological Society, p. 94-130.

Donnellan, A., Hager, B.H., King, R.W., and Herring, T.A., 1993, Geodetic measurement of deformation in the Ventura basin region, southern California: Journal of Geophysical Research, v. 98, p. 21,727-21,739.

Dreger, D., and Helmberger, D., 1991, Source parameters of the Sierra Madre earthquake from regional and local body waves: Geophysical Research Letter, v. 18, p. 2015-2018.

Dreger, D., and Helmberger, D.V., 1991, Complex faulting deduced from broadband modeling of the Feb. 28, 1990 Upland earthquake (M_L=5.2): Bulletin Seismological Society of America, v. 81, p. 1129-1144.

Dreger, D.S., 1994, Empirical Green's function study of the January 17, 1994 Northridge, California earthquake (M_w6.7): Geophysical Research Letter, v. 21, p. 2633-2636.

Fiegl, K. L., Agnew, D.C., Bock, Y., and Dong, D., and others, 1993, Space geodetic measurement of crustal deformation in central and southern California, 1984-1992: Journal of Geophysical Research, v. 98, p. 21,677-21,712.

Gutenberg, B., Richter, C.F., and Wood, H.O., 1932, The earthquake in Santa Monica Bay, California on August 30, 1930: Bulletin Seismological Society of America, v. 22, p. 138-154.

Hadley, D., and Kanamori, H., 1977, Seismic structure of the Transverse Ranges, California: Bulletin Seismological Society of America, v. 88, p. 1469-1478.

Hanks, T., and Kanamori, H., 1979, A moment magnitude scale: Journal of Geophysical Research, v. 84, p. 2348-2350.

Hauksson, E., 1990, Earthquakes, faulting and stress in the Los Angeles Basin: Journal of Geophysical Research, v. 95, p.15,365-15,394.

Hauksson, E., 1992, Seismicity, faults, and earthquake potential in Los Angeles, southern California, *in* Pipkin, B. and Proctor, R.J., eds., Engineering Geology Practice in Southern California, Belmont, California: Association of Engineering Geologists, Belmont, California, p. 167-179.

Hauksson, E., 1994, The 1991 Sierra Madre earthquake sequence in southern California – Seismological and Tectonic Analysis: Bulletin Seismological Society of America, v. 84, p. 1058-1074.

Hauksson, E., and Gross, S., 1991, Source parameters of the 1933 Long Beach earthquake: Seismological Society of America Bulletin, v. 81, p. 81-98.

Hauksson, E., and Jones, L.M., 1989, The 1987 Whittier Narrows earthquake sequence in Los Angeles, southern California – Seismological and Tectonic Analysis: Journal of Geophyical Research, v. 94, p. 9569-9590.

Hauksson, E., and Jones, L.M., 1991, The 1988 and 1990 Upland earthquakes – Left-lateral faulting adjacent to the Central Transverse Ranges: Journal of Geophysical Research, v. 96, p. 8143-8165.

Hauksson, E., Jones, L.M.,. Davis, T.L, Hutton, L.K., Brady, A.G., Reasenberg, P.A., Michael, A.J., Yerkes, R.F., Williams, P., Reagor, G., Stover, C.W., Bent, A.L., Shakal, A.K., Etheredge, E., Porcella, R.L., Bufe, C.G., Johnston, M.J.S., and Cranswick, E., 1988, The 1987 Whittier Narrows earthquake in the Los Angeles metropolitan area, California: Science, v. 239, p. 1409-1412.

Hauksson, E., and Saldivar, G.V., 1986, The 1930 Santa Monica and the 1979 Malibu, California, earthquakes: Bulletin Seismological Society of America, v. 76, p. 1542-1559.

Hauksson, E., and Saldivar, G.M., 1989, Seismicity and active compressional tectonics in the Santa Monica Bay, southern California: Journal of Geophysical Research, v. 94, p. 9591-9606.

Hauksson, E., Jones, L.M., and Hutton, K., 1995, The 1994 Northridge earthquake in California – Seismological and Tectonic Aspects: Journal of Geophysical Research, in press.

Heaton, T.H., 1982, The 1971 San Fernando earthquake – A double event?: Bulletin Seismological Society of America, v. 72, p. 2037-2062.

Heaton, T. H., and Helmberger, D.V., 1979, Generalized ray models of the San Fernando earthquake: Bulletin Seismological Society of America, v. 69, p. 1311-1341.

Hileman, J.A., Allen, C.R., and Nordquist, J.M., 1973, Seismicity of the southern California region, 1 January 1932 to 31 December 1972: Seismological Laboratory, California Institute of Technology, Pasadena, California.

Hudnut, K.W., Murray, M.H., Donnellan, A., Bock, Y., and others, 1994, Coseismic displacements of the 1994 Northridge, California, earthquake:1994 SSA Annual Meeting (abstracts), Pasadena, California.

Hutton, L.K., and Boore, D.M., 1987, The M_L Scale in southern California: Bulletin Seismological Society of America, v. 77, p. 2074-2093.

Hutton, L.K., and Jones, L.M., 1992, Local magnitudes and apparent variations in seismicity rates in southern California: Bulletin Seismological Society of America, v. 93, p. 313-329.

Ishida, M., and Kanamori, H., 1978, The foreshock activity of the 1971 San Fernando earthquake, California: Bulletin Seismological Society of America, v. 68, p.1265-1279.

Jennings, C.W., 1975, Fault map of California with volcanoes, thermal springs and thermal wells, 1:750,000 scale: California Department of Conservation, Division of Mines and Geology, Geologic Data Map 1.

Jones, L.M., 1984, Foreshocks (1966-1980) in the San Andreas System, California: Bulletin Seismological Society of America, v. 74, p. 1361-1380.

Jones, L.M., Sieh, K.E., Hauksson, E., and Hutton, L.K., 1990, The 3 December 1988 Pasadena, California earthquake – Evidence for strike-slip motion on the Raymond fault: Bulletin Seismological Society of America, v. 80, p. 474-482.

Kagan, Y.Y., and Jackson, D.D., 1994, Long-term probabilistic forecasting of earthquakes: Journal of Geophysical Research, v. 99, p. 13,685-13,700.

Kanamori, H., Mori, J., and Heaton, T.H., 1990, The December 3, 1988 Pasadena earthquake (M_L=4.9) recorded with the very broadband system in Pasadena: Seismological Society of America Bulletin, v. 80, p. 483-487.

Klein, F.W., 1985, User's guide to HYPOINVERSE, a program for VAX and PC350 computers to solve for earthquake locations: U.S. Geological Survey, Menlo Park, California, Open-File Report 85-515, 24 p.

Mori, J., Wald, D., and Wesson, R., 1995, Overlapping fault planes of the 1971 San Fernando and 1994 Northridge, California earthquakes: Geophysical Research Letter, in press.

Namson, J., and Davis, T., 1992, Late Cenozoic thrust ramps of southern California: Final Report to the Southern California Earthquake Center.

Proctor, R.J., Crook, R., McKeown, M.H., and Moresco, R.L., 1972, Relation of known faults to surface ruptures, 1971 San Fernando earthquake, southern California: Geological Society of America Bulletin, v. 83, p. 1601-1618.

Reasenberg, P., and Oppenheimer, D., 1985, FPFIT, FPPLOT and FPPAGE – FORTRAN computer programs for calculating and displaying earthquake fault-plane solutions: U.S. Geological Survey Open-File Report 85-739, 109 p.

Richter, C.F., 1958, Elementary Seismology: W.H. Freeman and Co., San Francisco, California, 768 p.

Roecker, S., and Ellsworth, W.L., 1978, VELEST, FORTRAN program report: U.S. Geological Survey.

Scientists of the U.S. Geological Survey and the Southern California Earthquake Center, 1994, The magnitude 6.7 Northridge, California, earthquake of January 17, 1994: Science, v. 266, p. 389-397.

Stein, R. S., King, G.C.P., and Lin, J., 1994, Stress triggering of the 1994 M=6.7 Northridge, California earthquake by its predecessors: Science, v. 265, p. 1432-1435.

Stein, R.S., and Yeats, R.S., 1989, Hidden earthquakes: Scientific American, p. 48-57.

Stierman, D.J., and Ellsworth, W.L., 1976, Aftershocks of the February 21, 1973, Point Magu, California earthquake: Bulletin Seismological Society of America, v. 66, p. 1931-1952.

Taber, S., 1920, The Inglewood earthquake in southern California, June 21, 1920: Bulletin Seismological Society of America, v. 10, p. 129-145.

Thatcher, W., Hileman, J.A., and Hanks, T.C., 1975, Seismic slip distribution along the San Jacinto fault zone, southern California, and its implications: Geological Society of America Bulletin, v. 86, p. 1140-1146.

Thio, H.-K., and Kanamori, H., 1995, Source complexity of the 1994 Northridge earthquake and its relation to aftershock mechanisms: to be submitted to the Bulletin Seismological Society of America.

Wald, D.J., and Heaton, T.H., 1994, A dislocation model of the 1994 Northridge, California, earthquake determined from strong ground motion: U. S. Geological Survey Open-File Report 24-278.

Webb, T.H., and Kanamori, H., 1985, Earthquake focal mechanisms in the eastern Transverse Ranges and San Emigdio Mountains, southern California and evidence for a regional decollement: Bulletin Seismological Society of America, v. 75, p. 737-757.

Wessel, P., and Smith, W.H.F., 1991, Free software helps map and display data: EOS Transactions, American Geophysical Union, v. 72.

Whitcomb, J.H., Allen, C.R., Garmany, J.D., and Hileman, J.A., 1973, San Fernando earthquakes series, 1971 – Focal Mechanisms and Tectonics: Review of Geophysics, v. 11, p. 693-730.

Wood, H.O., 1933, Preliminary report on the Long Beach earthquake: Bulletin Seismological Society of America, v. 23, p. 43-56.

Yeats, R.S., 1981, Quaternary flake tectonics of the California Transverse Ranges: Geology, v. 9, p. 16-20.

Yeats, R.S., 1987, Geology and seismicity of the eastern Red Mountain fault, Ventura county: U. S. Geological Survey Report 1339, p. 137-160.

Yeats, R.S., 1988, Late Quaternary slip rate on the Oak Ridge Fault, Transverse Ranges, California – Implications for seismic risk: Journal of Geophysical Research, v. 93, p. 12,137-12,149.

Yeats, R.S., 1993, Converging more slowly: Nature, v. 366, p. 299-301.

Yeats, R.S., and Huftile, G.J.,1995, Oak Ridge fault system and the 1994 Northridge, California, earthquake: Nature, v. 373, p. 418-420.

Ziony, J.I., and Jones, L.M., 1989, Map showing late Quaternary faults and 1978-1984 seismicity of the Los Angeles region, California: U.S. Geological Survey Miscellaneous Series Map MF-1964.

Ziony, J.I., and Yerkes, R.F., 1985, Evaluating earthquake and surface faulting potential, *in* Ziony, J.I., ed., Evaluating Earthquake Hazards in the Los Angeles Region - An Earth-Science Perspective: U. S. Geological Survey Professional Paper 1360, p. 43-91.

Dewey, J.W., Dengler, L., Reagor, B.G., and Moley, K., 1995, Spatial variations of intensity in the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 39-46.

SPATIAL VARIATIONS OF INTENSITY IN THE NORTHRIDGE EARTHQUAKE

by

J. W. Dewey[1], L. Dengler[2], B. G. Reagor[1], and K. Moley[2]

INTRODUCTION

We present maps of Modified Mercalli Intensities (MMI) for the Northridge, California, main shock of January 17, 1994. These maps characterize the severity of earthquake shaking at different locations on the basis of the effects of the shaking on people, manmade structures, and landscape at each location. The maps summarize and generalize the spatial distribution of macroseismic effects.

The data that form the basis of the current maps are given in much more detail in Dewey and others (1995). These data come from the authors' field observations, press reports, lists of damaged buildings identified by local building inspectors, published reports by civil and structural engineers, responses to mail questionnaires sent out by the U.S. Geological Survey (USGS), and responses to e-mail and phone surveys conducted by the Humboldt Earthquake Education Center of Humboldt State University.

The maps of Figures 1 and 2 are constructed to be similar to seismic intensity maps that have been produced for significant U.S. earthquakes by U. S. Government agencies since 1931. The intensity values plotted in the maps correspond to the effects observed or reported in rather large areas – usually communities or zip-code regions. Within communities or zip-code regions there is typically a large spatial variation of damage which in most cases is not represented on the maps. Occasionally we assign a single intensity value to an area as small as a several-block neighborhood of a community. When such small regions are singled out, it is usually because their damage is anomalously high relative to a broad surrounding area.

Our isoseismal maps are similar enough in appearance to the maps presented by Dengler and Moley (this volume) that it is worthwhile to emphasize their difference. The isoseismal maps of this paper represent the level of shaking as inferred from a number of different effects of the earthquake, whereas each figure Dengler and Moley (this volume) contours the pervasiveness of one specific effect.

[1]U.S. Geological Survey, Denver, Colorado
[2]Humboldt Earthquake Education Center, Humboldt State University, Arcata, California

Table 1. Modified Mercalli Intensity Scale of 1931 (Abridged; Wood and Neumann, 1931, p. 282-283). Some of the following criteria that describe human reactions or effects due to ground failure are no longer given significant influence in the assigning of intensity values.

I.	Not felt except by a very few under especially favorable circumstances.
II.	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III.	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV.	During the day felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V.	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.
VI.	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII.	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII.	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.
IX.	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI.	Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII.	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

MODIFIED MERCALLI INTENSITY SCALE OF 1931 AND ITS APPLICATION TO DAMAGE FROM THE 1994 EARTHQUAKE

Intensities assigned by the U. S. Geological Survey and (prior to 1973) by agencies in the U. S. Department of Commerce have for many decades been based on the Modified Mercalli Intensity (MMI) Scale of 1931 (Wood and Neumann, 1931), with amendments and modifications that have been developed since 1931. The scale as originally abridged by Wood and Neumann (1931) is given in Table 1. Amendments and modifications are necessary because experience with the MMI Scale has shown that some criteria are more reliable than others as indicators of the level of ground shaking. Moreover, construction methods have changed appreciably since the scale was introduced. In assigning intensities to the Northridge earthquake, we follow amendments and modifications that are summarized by Stover and Coffman (1993) and that have been used by the USGS to assign intensities in recent years. For post-1931 construction types, we follow precedent set in USGS intensity surveys of recent years. In the next section, we describe the effects that were most influential in assigning intensities to the Northridge earthquake.

BROAD-SCALE FEATURES OF THE DAMAGE DISTRIBUTION AND ISOSEISMAL MAPS

The highest intensity we have assigned is IX. To assign an intensity higher than IX to a location, we would have required that the following be characteristic of that location: well-built wooden structures severely damaged, with some destroyed; most masonry and frame structures destroyed with foundations. Since 1931 it has become clear that many phenomena that Wood and Neumann (1931) originally used as criteria to define the highest Modified Mercalli Intensities (X and above) are related less to the level of ground shaking than to the presence of ground conditions susceptible to spectacular failure or to the ease with which seismic faulting of different style and depth can propagate to the ground surface. Criteria based on such phenomena are downweighted now in assigning of intensities (Stover and Coffman, 1993).

Intensity IX was characteristic of 40 square km in Sherman Oaks, Northridge, Granada Hills, and along the I-5 corridor just east of the Santa Susana Mountains (Figure 3). Two neighborhoods of several blocks each in Santa Monica and west-central Los Angeles also experi-

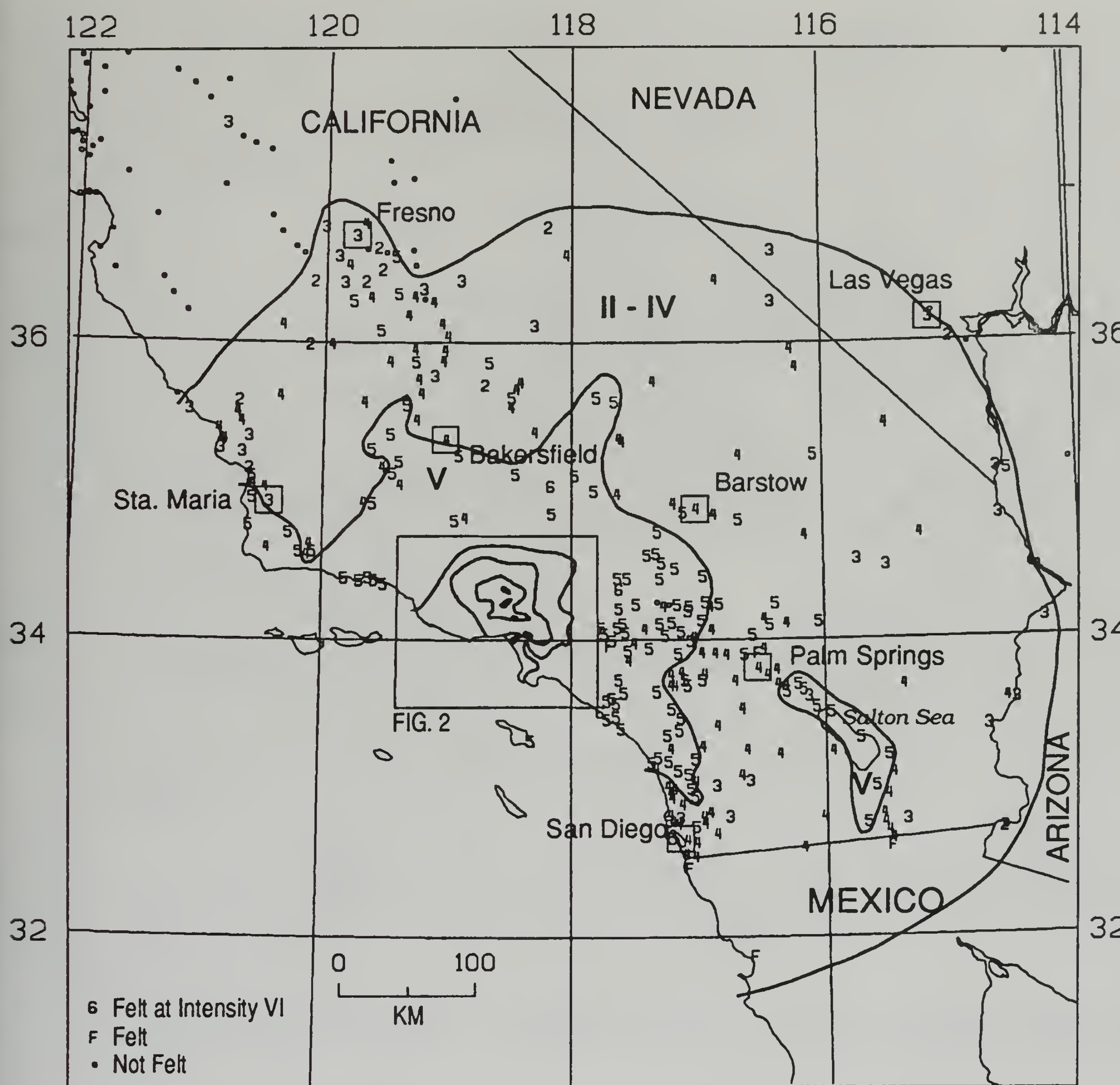


Figure 1. Far-field isoseismal map for the Northridge earthquake. Roman numerals give average MMI for the regions between isoseismals; Arabic numerals represent intensities in individual communities. Squares denote towns labeled in the figure. Box labeled "FIG. 2" identifies boundaries of that figure.

enced damage characteristic of intensity IX (Figure 2). Intensity IX was assigned on the basis of the following effects: multiple cases of structural damage to reinforced-concrete buildings and parking structures that would have been built when a seismic code was in effect, with some cases of partial or complete collapse; widespred destruction of wood-frame apartment buildings having large open areas in their first stories; collapse of elevated freeway sections. Effects due to ground failure were not used for assigning intensity IX (Stover and Coffman, 1993).

Intensity VIII was assigned on the basis of the following effects: considerable damage to unreinforced masonry buildings, with partial collapse; old wood-frame houses shifted off foundations; damage to wood-frame apartment buildings having open first-stories, with some cases of apartments being destroyed; significant damage to reinforced, lined, masonry chimneys on single-family homes; structural damage to some reinforced-concrete structures that would have been built when a seismic code was in effect; very heavy furniture moved conspicuously or overturned. These effects were observed at

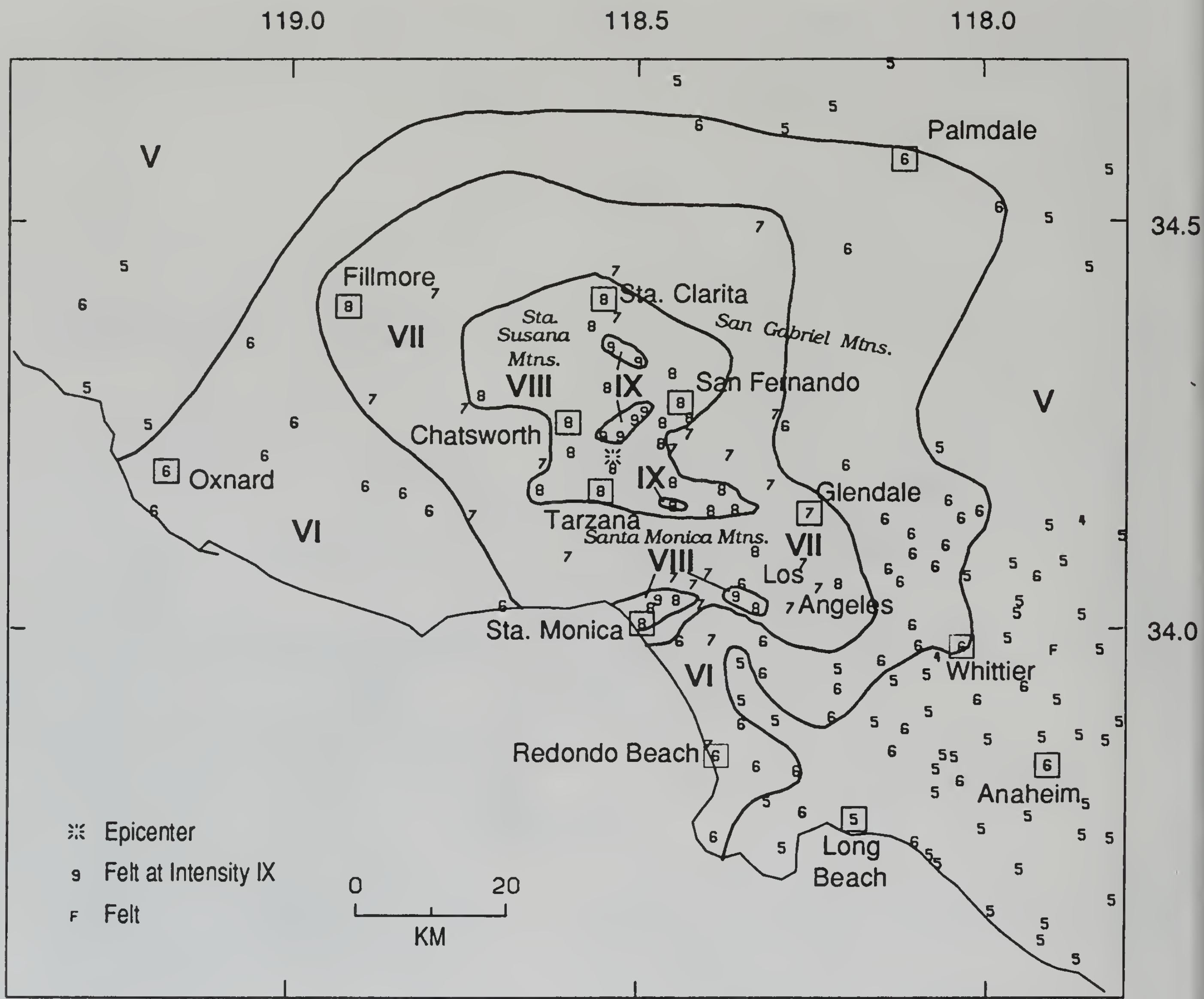


Figure 2. Distribution of MMI in the epicentral region. Roman numerals give average MMI within isoseismals. Arabic numerals represent intensities at specific locations. Squares denote towns labeled in the figure.

many locations over a broad area of the San Fernando Valley, and also in parts of Santa Clarita, Simi Valley, Santa Monica, and west central Los Angeles. Outside of the regions enclosed by intensity VIII isoseismals, damage characteristic of intensity VIII occurred at Fillmore, at the University of Southern California/County Hospital complex in Los Angeles, and in a 3 km long, several blocks wide, area of Hollywood along Hollywood Boulevard. In some areas, reports of shattered earth and rockfall activity (R. Jibson and E. Harp, USGS, personal communication) were used to interpolate the intensity VIII isoseismal through mountainous regions that separate population centers. Otherwise, effects due to ground failure were not used for assigning intensity VIII (Stover and Coffman, 1993).

Intensity VII was assigned on the basis of the following effects: significant damage to unreinforced masonry (URM) buildings, including cracks in bearing walls and out-of-plane movement or fall of upper walls and parapets; many URM chimneys fallen or broken at the roofline; some masonry fences fallen or destroyed; heavy furniture overturned. In some areas, reports of landslide and

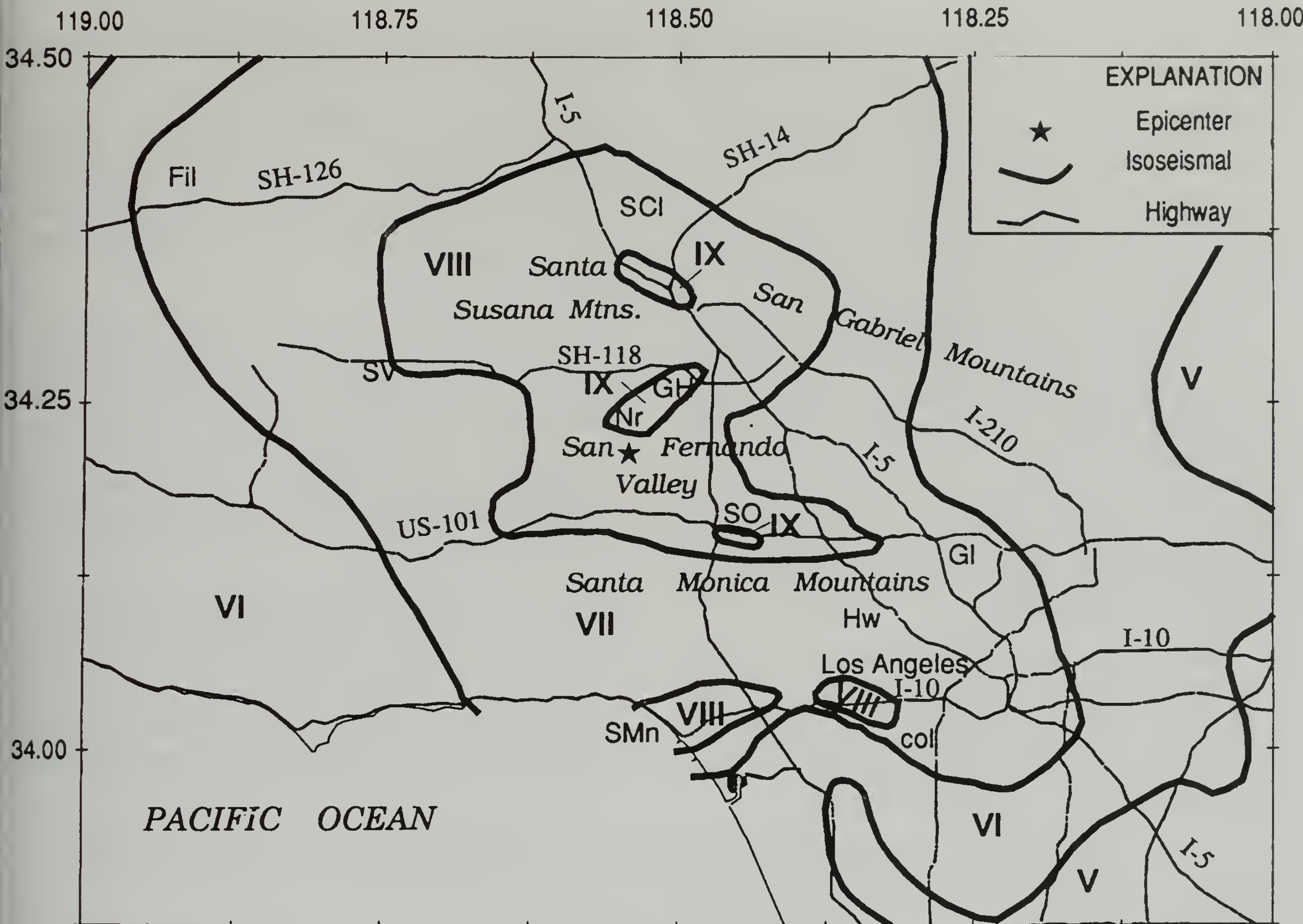


Figure 3. Location of higher isoseismals with respect to major roads. Abbreviations for towns and sites: "col" - Los Angeles Coliseum; "Fil" - Fillmore; "GH" - Granada Hills; "Gl" - Glendale; "Hw" - Hollywood; "Nr" - Northridge; "SCl" - Santa Clarita; "SO" - Sherman Oaks.

rockfall activity (R. Jibson and E. Harp, personal communication) were used to interpolate the intensity VII isoseismal through mountainous regions that separate population centers; otherwise effects known to be due to ground failure were not used for assigning intensity VII (Stover and Coffman, 1993).

There were individual cases of costly or spectacular damage within areas that were generally characterized by intensity VII. These included partial collapses of parking structures in Glendale and downtown Los Angeles, and major damage to the Los Angeles Memorial Coliseum. There were likewise pockets of high damage in residential areas of the Santa Monica Mountains that were otherwise characterized by intensity VII.

Intensity VI was assigned on the basis of the following effects: some windows broken out; a few instances of fallen plaster or damaged unreinforced masonry (URM) chimneys; large cracks in interior walls; many small objects overturned and fallen; many items thrown from store shelves; many glassware items or dishes broken; light furniture overturned and moderately heavy furniture displaced. Effects on people were not used to assign intensities of VI or above (Stover and Coffman, 1993). Unusually spectacular effects from within the intensity VI isoseismals included damage from spreading and subsidence of fill at the Kings Harbor Marina in Redondo Beach.

Intensity V was assigned on the basis of the following effects: a few small objects overturned and fallen; a few items thrown from store shelves; hairline cracks in interior walls; a few windows cracked; hanging pictures tilted, out of place, or fallen; trees and bushes shaken moderately to strongly; observer reported difficulty standing or walking; felt moderately by people in moving vehicles. Most effects in the original scale that pertain to perceptions of the strength of the earthquake, or to the extent that people were frightened or awakened by the earthquake, were not used as criteria for this or higher intensities (Stover and Coffman, 1993). The spectacular collapse of the Anaheim stadium scoreboard structure took place in a region in which most communities were characterized by intensity V effects (Figure 2).

Intensity IV was assigned on the basis of the following effects: felt by many to all; trees and bushes shaken slightly; buildings shaken moderately to strongly; walls creaked loudly; observer described the shaking as "strong" (Stover and Coffman, 1993).

Intensity III was assigned according to the original criteria of Wood and Neumann (1931): "Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated."

Intensity II was assigned according to the original criteria of Wood and Neumann (1931): "Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing."

At some locations the earthquake was felt, but observations are insufficient to assign an intensity. The maps show an "F" at such locations.

Intensity I, "Not felt except by a very few under especially favorable circumstances" (Wood and Neumann, 1931), was not assigned for the Northridge earthquake.

EFFECT OF THE EARTHQUAKE ON PEOPLE AND HOUSEHOLDS

People in the regions covered by intensity VIII and IX isoseismals commonly described the shaking as "violent" and commonly reported major disruption to the contents of their homes, even in the many cases in which the homes were not structurally damaged.

An observer in Northridge reported: "After getting my family to safety in front yard, checking on neighbors and triaging the house damage, I was in shock until next day; unable to keep food down, hot/cold flashes. Most furniture overturned, spilling out contents such as china and crystal. The kitchen was a big mess, with broken glass/food items all over the floor."

From Chatsworth: "This is the single scariest time in my life. After the quake I ran to my children through broken glass barefoot. I'm not the only parent to do so. I have yet to return surviving crystal to my breakfront or pictures to my walls. I need to find a rental house and move out during reconstruction. For me the `earthquake' is not over."

From western Los Angeles near the boundary between intensity VII and intensity VIII regions: "We were awakened not only by the motion but by the noise — the walls were moving, furniture shifting on wood floors, books thrown from shelves, glass being thrown and breaking — it was an assult on all of the senses except visual, for it was still very dark and any remaining lights went out immediately."

Although the perceived strength of shaking predictably decreased with increasing distance from the epicentral region, people even in intensity V regions experienced the shaking as sufficiently strong that they inspected their houses for damage. In one tragedy in an intensity V location 90 km southeast of the epicenter, a woman rushing to be with her baby was killed when she slipped on a toy and hit her head on the child's crib.

COMPARISON WITH THE 1971 SAN FERNANDO EARTHQUAKE

The intensity pattern of the M_w = 6.7 1994 Northridge earthquake is broadly similar to that of the nearby M_w = 6.6 San Fernando earthquake of February 9, 1971 (Figure 4); like the 1994 earthquake, the 1971 earthquake occurred as a result of reverse faulting. To the extent that isoseismals depend on earthquake magnitude, gross character of faulting, and average attenuation of strong ground-motion with distance from the source, the isoseismals for the two earthquakes should be similar.

In detail, the isoseismals do differ. The intensity VII and VIII isoseismals of the Northridge earthquake enclose larger areas than the corresponding isoseismals of the San Fernando earthquake, whereas the intensity V and VI isoseismals of the Northridge earthquake enclose smaller areas than those of the San Fernando earthquake. The maximum intensity assigned to the Northridge earthquake was IX; the maximum intensity assigned to the San Fernando earthquake was XI. Considered as a group, these differences between the 1971 and 1994 isoseismals likely reflect: (1) real differences in the level of ground shaking; (2) systematic changes over time in

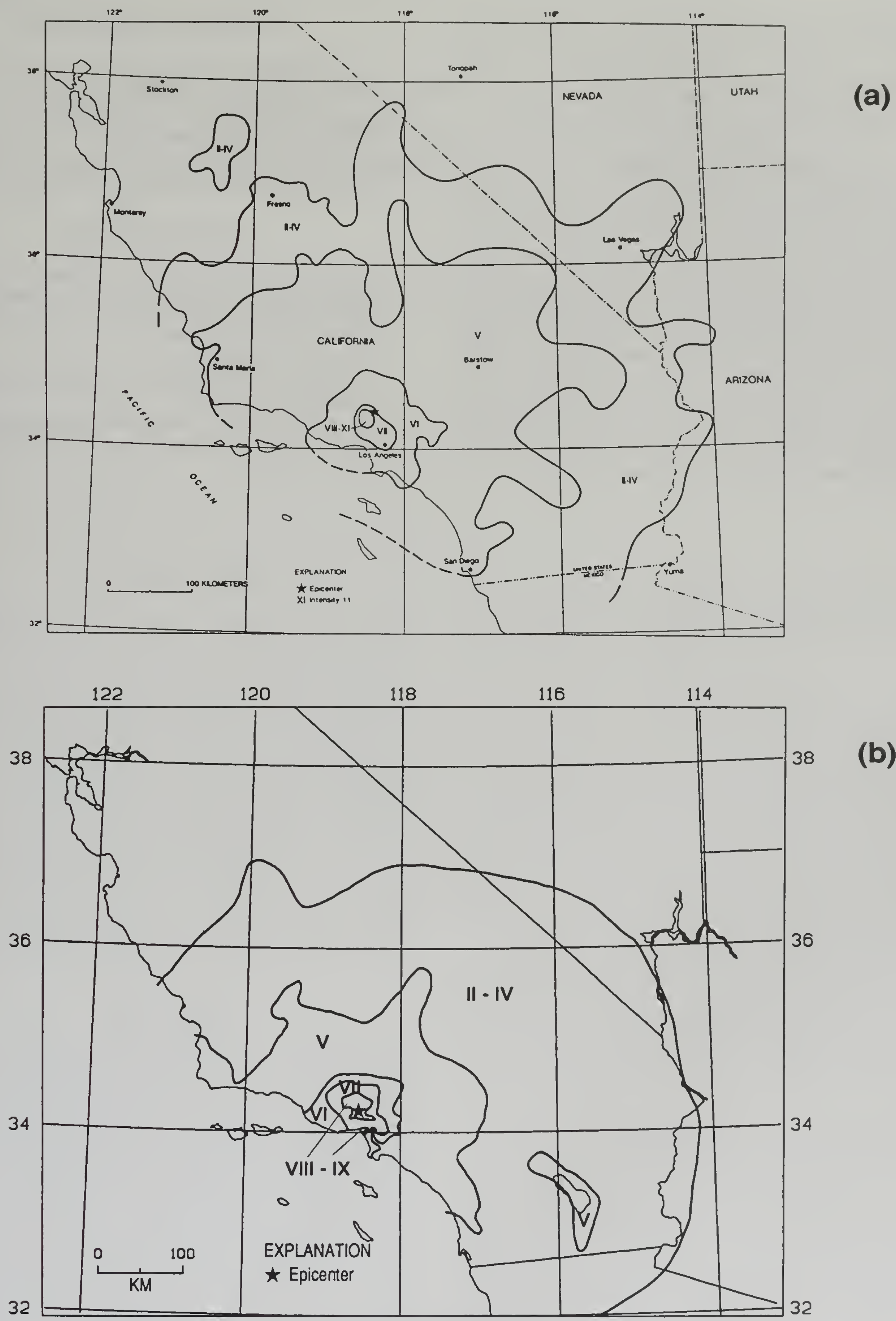


Figure 4. (a) Isoseismals of the San Fernando earthquake of 1971 (Stover and Coffman, 1993); (b) Isoseismals of the 1994 Northridge main shock, plotted to same scale as (a).

the damage susceptibility of the stock of human-made structures; (3) differences in the distribution of observations; (4) efforts to maximize consistency over time notwithstanding, differences in the way specific effects are interpreted in terms of the MMI scale.

The following differences between the sources of the two earthquakes are examples of those that could result in real differences in the level of ground shaking: (A) the locations of the energy release in the two shocks differed by about 20 km; (B) the 1971 fault rupture nucleated at depth beneath a lightly populated mountain range and propagated southward towards a heavily populated valley, whereas the 1994 fault rupture nucleated at depth beneath a heavily populated valley and propagated northward towards a region of lightly populated hills and moderately populated valleys; (C) the primary 1971 fault rupture broke through to the ground surface, whereas the primary 1994 fault rupture apparently terminated several kilometers below the ground surface.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of the many residents of the earthquake region who answered our questionnaires or sent us first-person accounts of their experiences. We thank Arthur C. Tarr for his help in applying geographic information systems technology to important steps in the preparation of figures.

REFERENCES

Dewey, J.W., Reagor, B.G., Dengler, L., and Moley, K., 1995, Intensity distribution and isoseismal maps for the Northridge, California, earthquake of January 17, 1994: U. S. Geological Survey Open-File Report 95-92, 35 p.

Stover, C.W., and Coffman, J.L., 1993, Seismicity of the United States, 1568-1989 (Revised): U. S. Geological Survey Professional Paper 1527, 418 p.

Wood, H.O., and Neumann, Frank, 1931, Modified Mercalli Intensity Scale of 1931: Seismological Society of America Bulletin, v.21, no.4, p. 277-283.

Dengler, L. and Moley, K.., 1995, A dense survey of individual perceptions, reactions, and observations of the January 17, 1994 Northridge earthquake *in* Woods, Mary C., and Seiple, W Ray, eds., The Northridge California Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 47-53.

A DENSE SURVEY OF INDIVIDUAL PERCEPTIONS, REACTIONS, AND OBSERVATIONS OF THE JANUARY 17, 1994 NORTHRIDGE EARTHQUAKE

by

Lori Dengler[1] and Kathy Moley[1]

INTRODUCTION

A survey of approximately 6,000 adults within the felt region of the January 17, 1994, Northridge earthquake was conducted between January 23 and May 5, 1994. The aim of this study was to provide data for the Modified Mercalli Intensity (MMI) study (see Dewey and others, this volume), and to improve planning for future earthquakes by obtaining a better understanding of how people are affected by different levels of ground shaking. The Northridge earthquake was felt by approximately 12 million people within an area of about 212,000 km^2. Over 99 percent of the region's residents were indoors at the time of the earthquake and about 85 percent were asleep. The very large number of persons in essentially the same situation makes this a particularly useful earthquake for intensity studies.

METHODS

An intensity questionnaire has been developed with the intent that it can be asked quickly over the telephone and assess an individual's experience of an earthquake (Dengler and Moley, 1994). Respondents were asked if they felt the earthquake; if they were awakened; the relative strength of ground shaking, on a scale of 0 (not felt) to 5 (violent); their reaction, on a scale of 0 (not felt) to 5 (panic); if they perceived it difficult to stand or walk; if pictures were knocked askew; if furniture moved; if items fell off of shelves, on a scale of 0 (none) to 3 (everything fell); and if there was any damage to structures, on a scale of 0 (none) to 3 (major damage). In addition to questions regarding the effects of the ground shaking all respondents were asked if they would like a copy of our study when completed.

Previous intensity studies (Dengler and others, 1993) have shown that as time passes individuals within the weakly felt regions of an earthquake are less likely to remember the effects and are less willing to participate in a telephone study. For these reasons, the first four weeks after the earthquake our telephone study concentrated exclusively on communities 150 km and further from the epicenter. Communities between 75 and 150 km away from the epicenter were surveyed during the following six weeks, and communities between 75 km and the epicenter were surveyed within the last two months of data collection. In addition to the reasons stated above, this pattern of data collection was employed not only because persons in the most strongly-felt areas have a longer retention of the earthquake's effects, but also to be sensitive to individual trauma suffered by those in the epicentral area.

Lists of telephone numbers for particular communities were compiled either from printed telephone directories or from a reverse telephone directory on CD-rom. From these lists, telephone numbers were selected at random and called by students who have been trained in phone survey techniques. Previous studies suggested that 20 or more respondents per community give stable average responses (Dengler and Moley, 1994).

[1]Humboldt Earthquake Education Center, Humboldt State University, Arcata, California

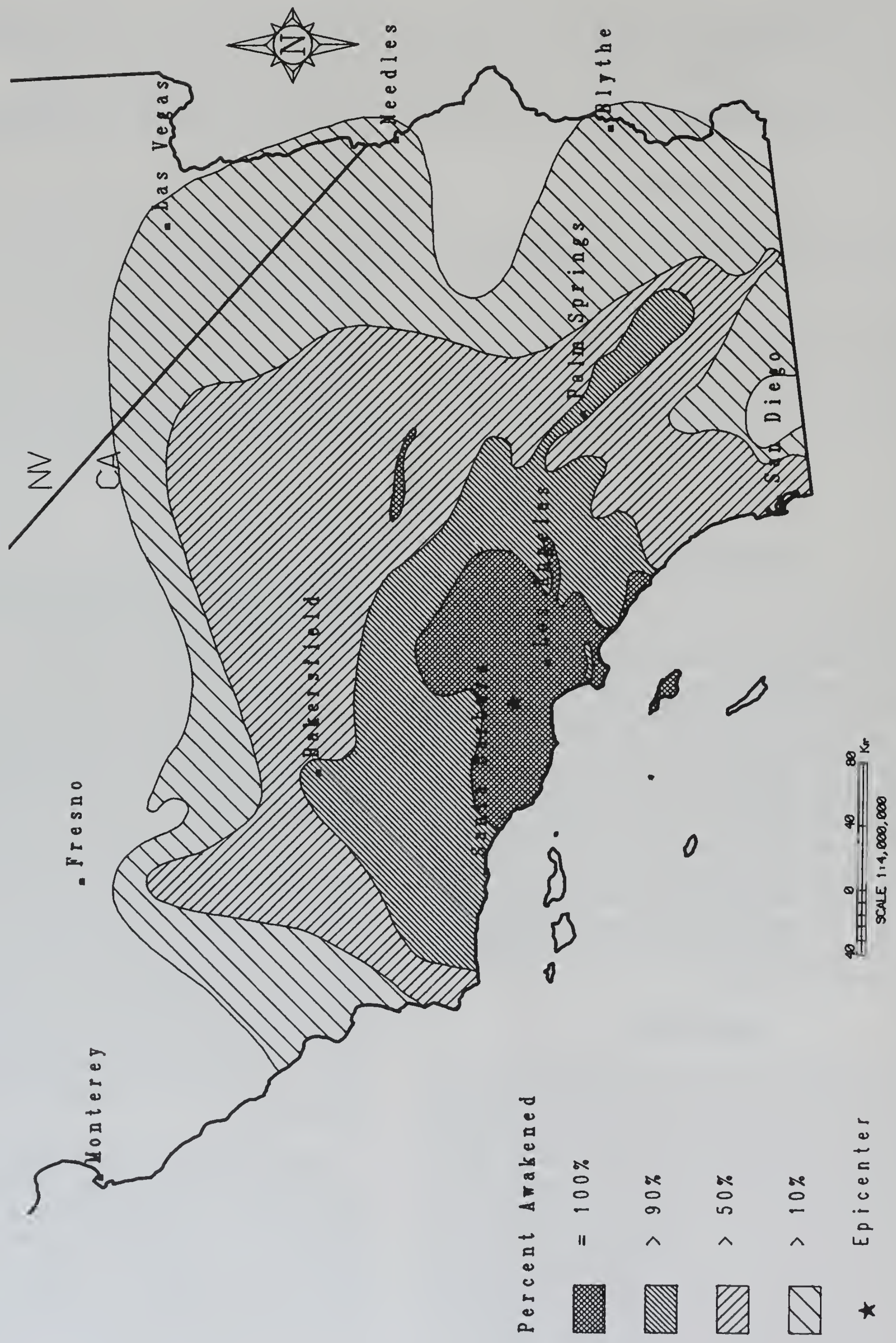


Figure 1. Percent awakened. Contours >10%, >50%, >90%, and 100% of persons who were awakened by the Northridge earthquake.

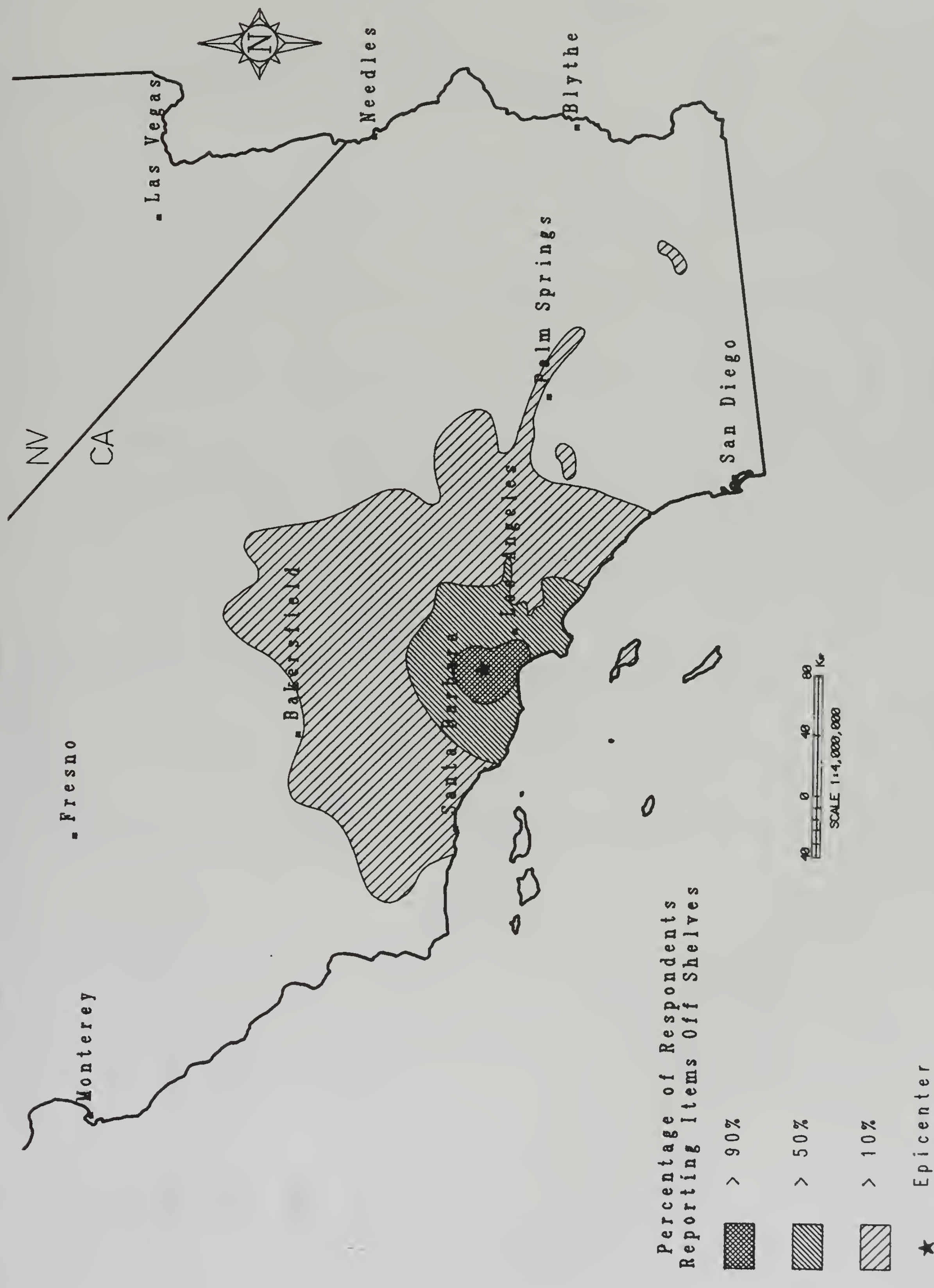


Figure 2. Percent reporting items knocked off shelves. Contours >10%, >50%, and >90% of respondents reporting any items knocked over or off of shelves.

Figure 3. Percent reporting damage to structures. Contours >10%, >50%, 75%, and >90% of respondents reporting any damage to structures.

Table 1. Responses for selected communities

COMMUNITY	Epicentral[1] Distance (km)	Number of[2] respondents	Percent[3] awakened	Perception[4] of shaking	Respondents[5] reaction	Percent[6] shelves	Percent[7] furniture	Percent[8] damage
Northridge	2	24	100.0	4.6	3.4	98.8	95.8	100.0
North Hollywood	15	22	100.0	4.4	3.6	95.5	72.7	71.4
Newhall	18	22	100.0	4.6	3.5	100.0	95.5	81.0
Simi Valley	18	26	100.0	4.6	3.1	100.0	88.5	64.0
Santa Monica	22	23	100.0	4.5	3.1	100.0	87.0	82.6
Glendale	25	29	100.0	4.6	3.7	86.2	41.4	48.1
Los Angeles	30	41	100.0	3.8	2.4	76.2	39.0	45.9
Pasadena	35	20	100.0	3.7	2.4	90.0	10.0	55.0
Whittier	52	22	100.0	4.0	2.5	81.8	36.4	22.7
Long Beach	58	26	100.0	3.8	1.9	57.7	19.2	12.5
Oxnard	65	40	100.0	3.9	2.7	67.5	10.0	20.0
Ventura	70	22	100.0	3.6	1.5	36.4	9.1	40.9
Anaheim	70	25	95.0	3.6	2.4	24.0	0.0	8.3
Pomona	77	23	95.5	3.3	2.0	21.7	8.7	13.0
Santa Anna	80	30	83.3	3.2	2.5	34.6	13.0	20.0
Riverside	105	57	87.2	3.3	1.6	19.3	3.6	3.5
Santa Barbara	106	51	95.8	3.5	2.1	20.0	2.0	4.0
San Bernardino	110	46	93.9	3.0	1.9	15.6	2.3	8.9
Bakersfield	130	48	92.1	3.0	1.5	4.2	2.1	7.1
Big Bear City	157	21	94.7	2.9	2.0	14.3	9.5	4.8
Oceanside	157	28	95.8	2.8	1.5	3.6	3.6	0.0
Barstow	160	23	100.0	2.5	1.6	4.3	4.3	0.0
Banning	166	20	86.7	1.9	1.4	5.0	5.0	15.0
Ridgecrest	170	32	88.9	2.1	1.2	12.5	0.0	3.1
Palm Springs	190	27	96.0	3.2	1.9	3.7	3.7	0.0
San Diego	200	54	58.3	1.9	1.1	1.9	0.0	1.9
Joshua Tree	203	34	78.6	1.8	1.1	2.9	0.0	0.0
Indio	220	25	90.9	2.4	1.4	12.0	0.0	4.0
San Luis Obispo	222	30	15.4	0.3	0.3	0.0	0.0	0.0
Twentynine Palms	227	21	27.8	1.0	0.6	9.5	0.0	4.8
Visalia	239	20	31.3	0.7	0.5	0.0	0.0	0.0
El Centro	313	23	52.6	1.6	1.0	0.0	0.0	0.0
Needles	360	20	12.5	0.3	0.2	0.0	0.0	0.0
Blythe	360	29	23.1	0.7	0.5	0.0	3.4	0.0
Las Vegas	370	33	40.0	1.4	0.7	3.0	0.0	0.0

[1]Epicentral Distance: approximate distance from the community to the epicenter.
[2]Number of respondents: total number of telephone surveys from persons in the community listed.
[3]Percent awakened: percentage of sleeping respondents who were awakened by the earthquake.
[4]Perception of shaking: the average of individual responses rated as follows:
0 = not felt 1 = weak 2 = mild
3 = moderate 4 = strong 5 = violent

[5]Respondent's reaction: the average of individual responses rated as follows:
0 = not felt 1 = very little reaction 2 = excited
3 = somewhat frightened 4 = very frightened 5 = panic
[6]Percent shelves: the percentage of persons reporting any items off shelves.
[7]Percent furniture: the percentage reporting furniture or heavy items being displaced by the earthquake.
[8]Percent damage: the percentage reporting any damage to structures.

Table 2. Effects and observations as a function of Modified Mercalli Intensity.

MMI[1]	Number of[2] respondents	Percent[3] awakened	Percent[4] shelves	Percent[5] furniture	Percent[6] damage	Percent[7] mod. dmg.	Percent[8] major dmg.
II	97	15.4	0.0	0.0	1.0	0.0	0.0
III	281	30.9	2.5	0.7	1.5	0.0	0.0
IV	1638	69.3	5.9	1.2	2.6	0.0	0.0
V	2248	89.2	23.2	2.7	7.3	0.3	0.0
VI	694	99.0	60.3	11.8	19.4	1.0	0.1
VII	171	100.0	91.2	55.0	55.8	7.6	3.5
VIII	328	100.0	98.2	86.2	83.1	29.0	12.2
IX	84	100.0	98.8	89.3	86.6	40.5	10.7

[1]MMI: Modified Mercalli Intensity
[2]Number of respondents: number of survey responses in this MMI category
[3]Percent awakened: percentage of those asleep who were awakened by the earthquake
[4]Percent shelves: percentage who reported any items knocked off shelves
[5]Percent furniture: percentage who reported furniture or heavy objects moving or becoming displaced
[6]Percent damage: percentage who reported any damage to structure
[7]Percent mod. dmg.: percentage reporting moderate structural damage
[8]Percent major dmg.: percentage reporting major structural damage

Table 3. Perception and reactions as a function of Modified Mercalli Intensity.

MMI[1]	Perception[2] of shaking	Percent[3] "weak/mild"	Percent[4] "violent"	Respondents[5] "reaction"	Percent[6] "little react"	Percent[7] "panic"	Requested[8] report
II	0.4	62.5	0.0	0.2	87.5	0.0	22.7
III	0.7	52.7	0.0	0.4	85.6	0.0	29.9
IV	2.0	38.5	1.2	1.2	60.7	0.3	38.5
V	3.0	18.5	2.6	1.7	46.5	1.7	44.8
VI	3.8	5.3	11.1	2.3	25.4	2.6	48.2
VII	4.4	0.6	46.8	3.2	8.2	11.7	52.4
VIII	4.6	0.0	65.2	3.3	6.1	15.2	64.8
IX	4.6	0.0	60.7	3.5	3.6	15.5	60.7

[1]MMI: Modified Mercalli Intensity
[2]Perception of shaking: average of all responses on a scale of 0 (not felt) to 5(violent)
[3]Percent "weak/mild": percentage of those who felt the earthquake describing it as "weak" or "mild"
[4]Percent "violent": percentage of those who felt the earthquake describing it as "violent"
[5]Respondents "reaction": average of all responses on a scale of 0 (not felt) to 5 (panic)
[6]Percent "little react": percentage of those who felt the earthquake having "little reaction" to it
[7]Percent "panic": percentage of those who felt the earthquke describing their reaction as "panic"
[8]Report requested: percentage of respondents who requested a report on our study

Over 18,000 total phone calls were made during the course of this study and of the nearly 60 percent of calls answered by a person, 55 percent were willing to participate in the study. Questionnaires have been designed so that responses are coded numerically. Questionnaire responses were entered on spread sheets and sorted by community and by the corresponding MMI value assigned by the U.S. Geological Survey (USGS) (Dewey and others, this volume). Average responses for each community and MMI category were determined.

In addition to the telephone survey, voluntary questionnaires were solicited from various electronic bulletin boards through Internet and through the U.S. Forest Service computer network. In this way, a data set consisting of approximately 1,500 questionnaires was collected. These voluntary questionnaires are being used in a microzonation study for the epicentral area currently in progress and as input for the MMI study (see Dewey, this volume).

RESULTS

Figures 1-3 map out the distribution of selected MMI indicators: the percentage of respondents per community who were awakened by the earthquake, the percentage of respondents reporting items toppled over or knocked of shelves, and the percentage of respondents reporting any damage to their structures. The maps show clear similarities to the Modified Mercalli isoseismal maps presented by Dewey and others (this volume), but differ in an important regard. The MMI maps are based on the composite effects of a number of shaking and damage indicators whereas Figures 1-3 all show the distribution of a single parameter or indicator of strong ground motion. The distribution of awakened sleepers most closely coincides to the weakest MMI isoseismals (IV); the distribution of items off shelves more closely coincides with the intermediate (V-VII) isoseismals. The distribution of damage corresponds closely to the highest isoseismals (VII-IX).

Table 1 summarizes responses for selected communities. In this table communities are listed in order of increased distance from the epicenter. With few exceptions, the general effects of the earthquake decrease with distance. Occasionally there are spikes within the data, such as communities located relatively the same distance from the epicenter, yet they stand out as being affected differently. Barstow, for example, is only six km closer to the epicenter than is Banning. Everyone spoken to in Barstow was awakened by the earthquake and only 87 percent of the respondents awoke in Banning. In this same example, however, 15 percent of the respondents in Banning reported at least some damage to their structure, whereas we received no reports of damage in Barstow. Las Vegas, the farthest community from the epicenter, has higher than expected values for categories, such as persons awakened, perception of shaking, and items off shelves. These elevated values are most likely a result of the number of respondents on floors other than the ground floor.

Tables 2 and 3 summarize responses by MMI. Most categories show steady increases as a function of MMI. Table 2 concentrates on observed effects. Differences between VIII and IX are relatively minimal, with the exception of the percentage of persons reporting moderate damage. It should be noted that the lower-than-expected number of respondents within the MMI II and III regions is a function of population density within these areas rather than sample populations (see figures 1 and 4, Dewey and others, this volume). Table 3 compares personal perception of shaking strength and reaction by MMI level. Respondents were given a choice of six descriptions for relative shaking strength which have assigned values from 0 to 5: not felt, weak, mild, moderate, strong, violent. A similar scale was used for their reaction: not felt, very little reaction, excitement, somewhat frightened, very frightened, and panic. Table 3 shows both the overall average perception of shaking and reaction, and also several subsets such as the percentage of persons feeling the earthquake who described it as "violent". Although the percent reporting "panic" increases with intensity, relatively few respondents describe their reaction in this way, even at the highest intensity levels. The last column shows the percentage of respondents who expressed an interest in receiving a report on this study. This column suggests that interest in earthquakes is proportional to how strong the ground shook.

ACKNOWLEDGMENTS

Brian Rassmussen (Humboldt State University) prepared the GIS maps presented in Figures 1-3. James Dewey (USGS) has provided invaluable critical review throughout this study. We appreciate the efforts of the many students who assisted with telephone calls and data entry. We thank the numerous individuals who distributed survey forms via electronic mail to businesses and classrooms, the USDA Forest Service, and all of the persons who contributed their stories. This study was partially supported by Humboldt State University, the California State University System, and the National Science Foundation.

REFERENCES

Dengler, L., and Moley, K., 1994, Toward a quantitative, rapid response estimation of intensities (abs.): Seismological Society of America, v. 65, p. 48.

Dengler, L., Moley, K., and Hutto, C., 1993, The pattern of ground shaking in the Sept. 20, 1993 Klamath Falls earthquakes (abs.): EOS, Transactions of the American Geophysical Union, v. 74.

SECTION II
Earthquake Effects

Darragh, R., Shakal, A. and Huang, M., 1995, Strong ground motion data from the 1994 Northridge, California, earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 55-63.

STRONG GROUND MOTION DATA FROM THE 1994 NORTHRIDGE, CALIFORNIA, EARTHQUAKE

by

Robert Darragh[1], Anthony Shakal[1] and Moh Huang[1]

INTRODUCTION

The 6.7 M (moment magnitude) earthquake that occurred near Northridge, California on January 17, 1994 produced an important set of strong-motion recordings. Strong-motion records were obtained from over 700 stations. These stations include more than 250 ground-response stations, 400 buildings, and 50 other structures.

Some of the highest acceleration ever recorded at ground-response and structural sites occurred in the Northridge earthquake. These accelerations are greater than most existing attenuation models would have predicted and are also higher than the 1971 San Fernando earthquake. The thrust mechanism of this event as well as its location under a metropolitan area may have contributed to the number of high acceleration recordings. Although the accelerations are high, the correspondence between measured acceleration and damage requires further study, since some sites with high acceleration experienced only moderate damage. Some vertical accelerations were larger than the horizontal, but in general this event fits the pattern observed in previous earthquakes. Strong-motion records processed to date show significant differences in acceleration and velocity waveforms and amplitudes across the San Fernando Valley.

SMIP STRONG-MOTION RECORDS

Strong-motion records were recovered from a total of 193 stations of the Strong Motion Instrumentation Program (SMIP) after the Northridge earthquake (Shakal and others, 1994a). The epicentral distance of the stations ranges from 5 km for the closest (Tarzana) to about 270 km for the farthest (Bombay Beach in Imperial County). The 193 stations include 116 ground-response stations and 77 extensively-instrumented structures. The extensively-instrumented structures include 57 buildings, 12 dams, 5 major freeway interchanges, a toll bridge, an airport control tower, and a power plant.

The SMIP stations that recorded this earthquake are shown on the map in Figure 1. Each station is identified by a three-digit code on the map. The maximum acceleration values, epicentral distance, sensor orientations and the station parameters are given in Shakal and others (1994a).

The results of the digitization and processing of the 49 ground-response records completed to date are presented in six SMIP processed data reports (Darragh and others, 1994a-d,f,i). In addition, SMIP has processed the records from twelve buildings and the results are presented in three SMIP processed data reports (Darragh and others, 1994e,g,h).

[1]California Department of Conservation, Division of Mines and Geology, Strong Motion Instrumentation Program, Sacramento, California

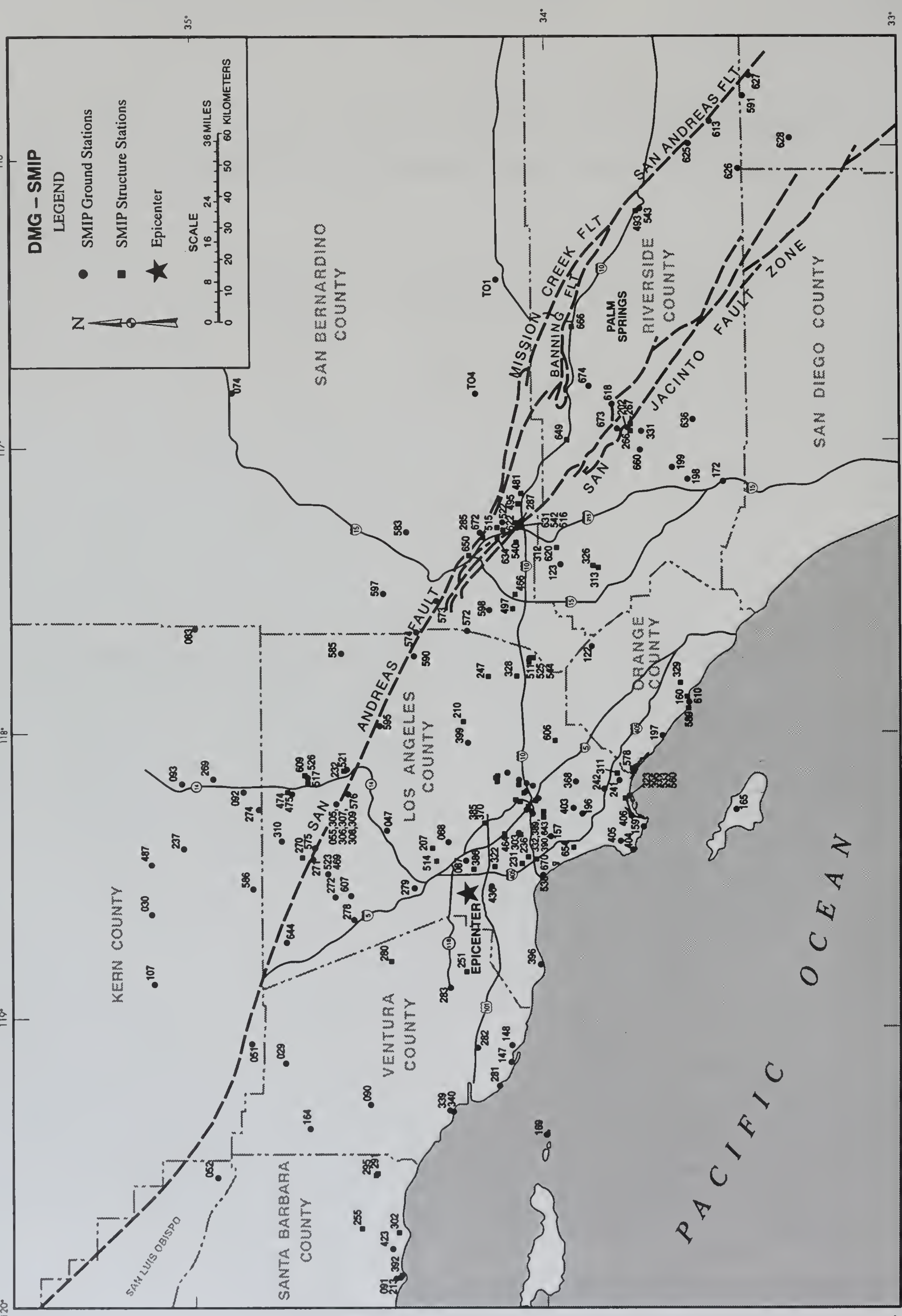


Figure 1. SMIP stations which recorded the Northridge earthquake of January 17, 1994.

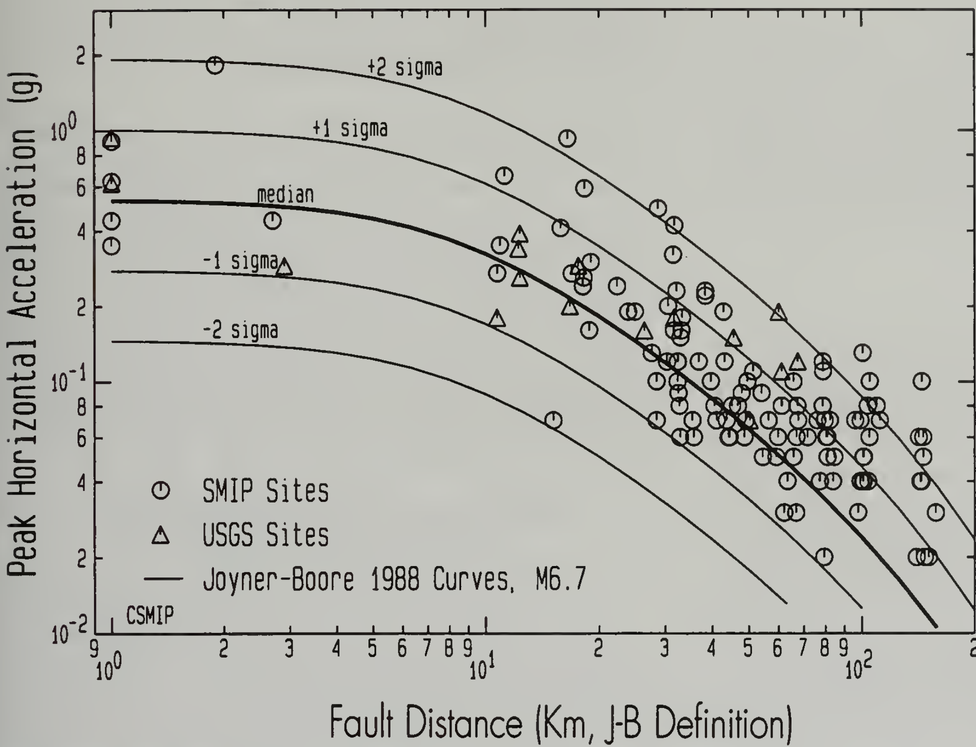


Figure 2. Maximum horizontal acceleration versus distance for the Northridge earthquake. Distance is from the surface projection of the aftershock zone, as defined by Joyner and Boore (1988). Largest of the two horizontal components is plotted. Bold line is the median curve of Joyner and Boore (1988) for a 6.7 M earthquake. Light lines indicate ±1 and ±2 standard deviation. Circles indicate SMIP stations, triangles indicate USGS stations.

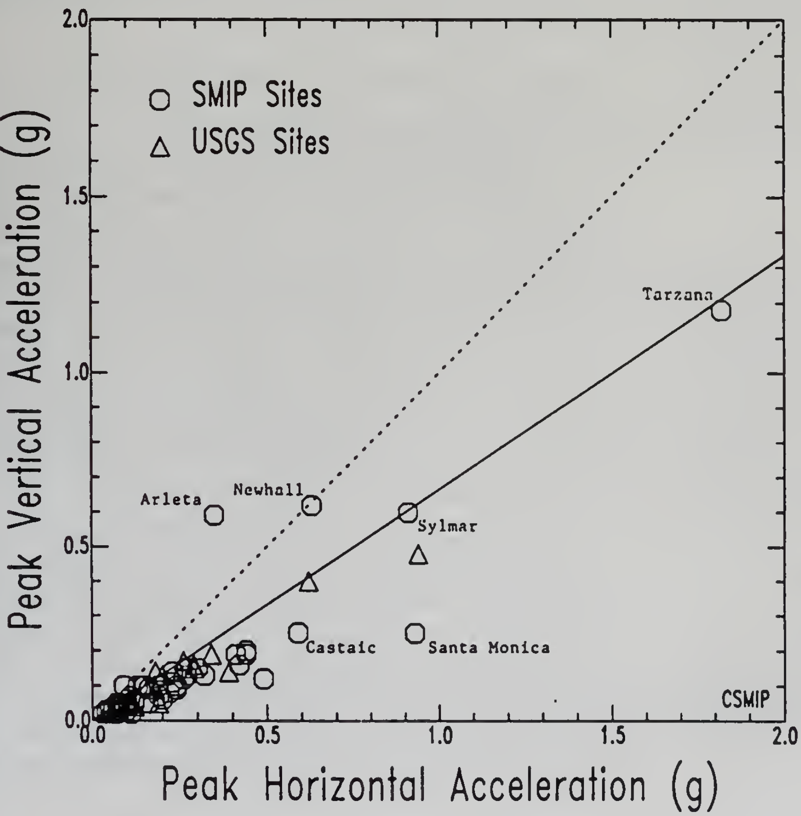


Figure 3. Maximum horizontal acceleration versus maximum vertical acceleration. The solid line is for vertical acceleration equal to two-thirds of the horizontal acceleration, the dashed line is for vertical acceleration equal to the horizontal acceleration.

STRONG-MOTION RECORDS — GENERAL FEATURES

Several conclusions can be drawn from an analysis of the general features of the accelerograms recorded at 116 SMIP (Shakal and others, 1994a), 60 USGS (Porcella and others, 1994), 71 USC (Trifunac and others, 1994) and 3 LADWP ground-response stations (Lindvall Richter Benuska, 1994) during the Northridge earthquake. These conclusions are:

Maximum Acceleration

The maximum horizontal accelerations from this earthquake are compared to a standard attenuation relationship (Joyner and Boore, 1988) in Figure 2. The Northridge accelerations are greater than would have been predicted by this relationship and are also greater than those in the 6.6 M San Fernando earthquake, that occurred nearby in 1971. The tendency for observed strong-motion data to exceed values predicted by attenuation relationships was also documented for the 5.8 M Whittier earthquake (Shakal and others, 1988), 7.1 M Loma Prieta (Shakal and others, 1990) and the 7.3 M Landers and 6.4 M Big Bear earthquakes (Cramer and Darragh, 1994).

Vertical Acceleration

The maximum vertical acceleration is often, on average, about two-thirds of the peak horizontal acceleration. However, as occasionally occurs during other earthquakes at close-in distances, vertical accelerations were equal to or greater than the maximum horizontal acceleration at a few stations, as shown in Figure 3. In general, the Northridge earthquake fits the pattern of other earthquakes with regard to vertical accelerations.

Spectral Acceleration

The spectral acceleration for three recent California earthquakes at ground-response stations near the fault is shown in Figure 4. For reference, the spectral shape from the Uniform Building Code (UBC) is also shown. The spectral acceleration for the 6.7 M Northridge earthquake at the Sylmar and Newhall stations is significantly greater than both the 7.1 M Loma Prieta earthquake at the Santa Cruz station and the 7.3 M Landers earthquake at the Joshua Tree station.

Duration

The duration of strong shaking for three recent California earthquakes is shown in Figure 5 for the same stations as in Figure 4. The duration of strong shaking for the 6.7 M Northridge earthquake is about 10 seconds at Sylmar and Newhall. This is comparable to the durations for the 6.6 M San Fernando and 7.1 M Loma Prieta events, but significantly less than the 30-second duration of the 7.3 M Landers earthquake.

Site Amplification of Strong Ground Motion

No clear trend in amplification of ground motion at soil sites is apparent in the strong-motion data for the Northridge earthquake, in contrast to the 7.1 M Loma Prieta earthquake. (Tarzana and Arleta may be two examples of localized site response to strong ground shaking, as discussed further below). Further investigation of the effects of site geology and basin effects will be necessary to determine the role of local site conditions on ground motions and damage during this earthquake.

STRONG-MOTION RECORDS — LOCAL OBSERVATIONS

The recorded ground accelerations and processed velocities at five stations are selected to highlight important features of the ground-response data (Shakal and others, 1994b). The accelerations for these stations are shown in Figure 6 and the corresponding velocities are shown in Figure 7. The five stations, arraigned in increasing epicentral distance, are Tarzana (5 km south of the epicenter), Arleta (10 km east of the epicenter), Sylmar (16 km north-east of the epicenter), Newhall (20 km north of the epicenter) and Santa Monica (23 km south of the epicenter).

Spatial Distribution of Acceleration and Velocity

In Figures 6 and 7, the waveform amplitudes at these five stations are plotted with a common scale for direct comparison. The ground acceleration waveforms vary considerably with distance and azimuth from the earthquake. For example, the maximum accelerations at Tarzana and Santa Monica occur about 5 seconds after the shear-wave arrival. In contrast, at Arleta, Sylmar and Newhall the peak acceleration occurs within 1 to 2 seconds of the shear-wave arrival. Also, the maximum accelerations at these stations as a function of distance highlights the scatter in peak accelerations shown Figure 2.

Figure 7 shows that the ground velocities north of the epicenter (at Sylmar and Newhall) are dominated by simple, large amplitude pulses indicative of directivity caused by the northward and updip propagation of the fault rupture. In this region, located 10 to 25 km north-northeast of the epicenter, the ground velocities are among the largest ever recorded. For example, the peak horizontal ground velocity at the ground-response sta-

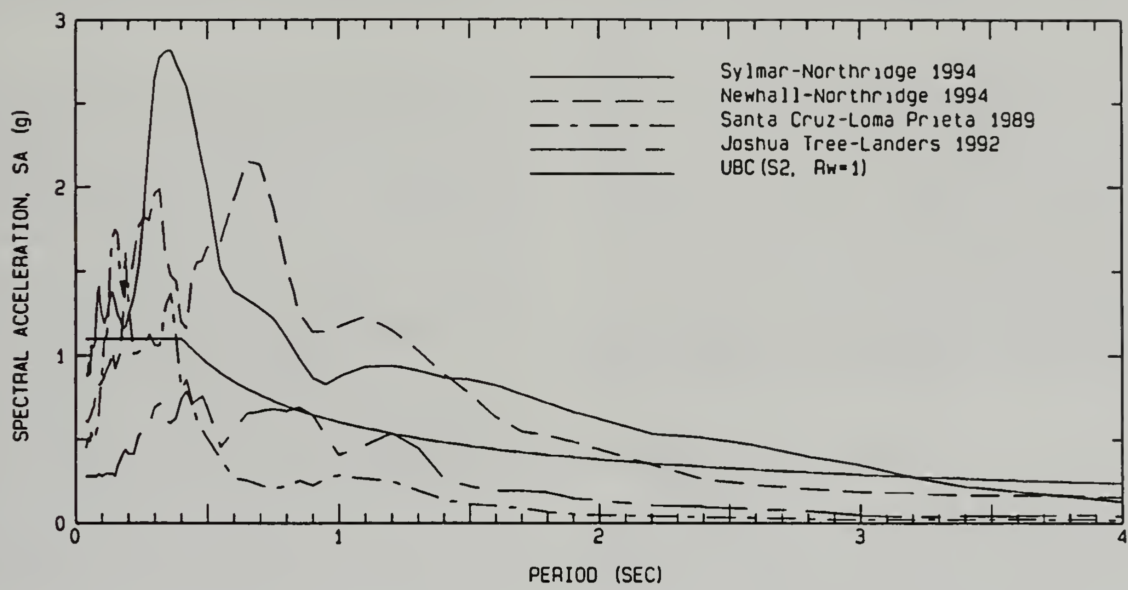


Figure 4. Spectral acceleration (5% damped) at similar distances (10 - 20 km) from the fault. Stations include Sylmar and Newhall for the 6.7 M Northridge earthquake, Santa Cruz for the 7.1 M Loma Prieta earthquake, and Joshua Tree for the 7.3 M Landers earthquake. The Uniform Building Code (UBC) spectrum is included for reference.

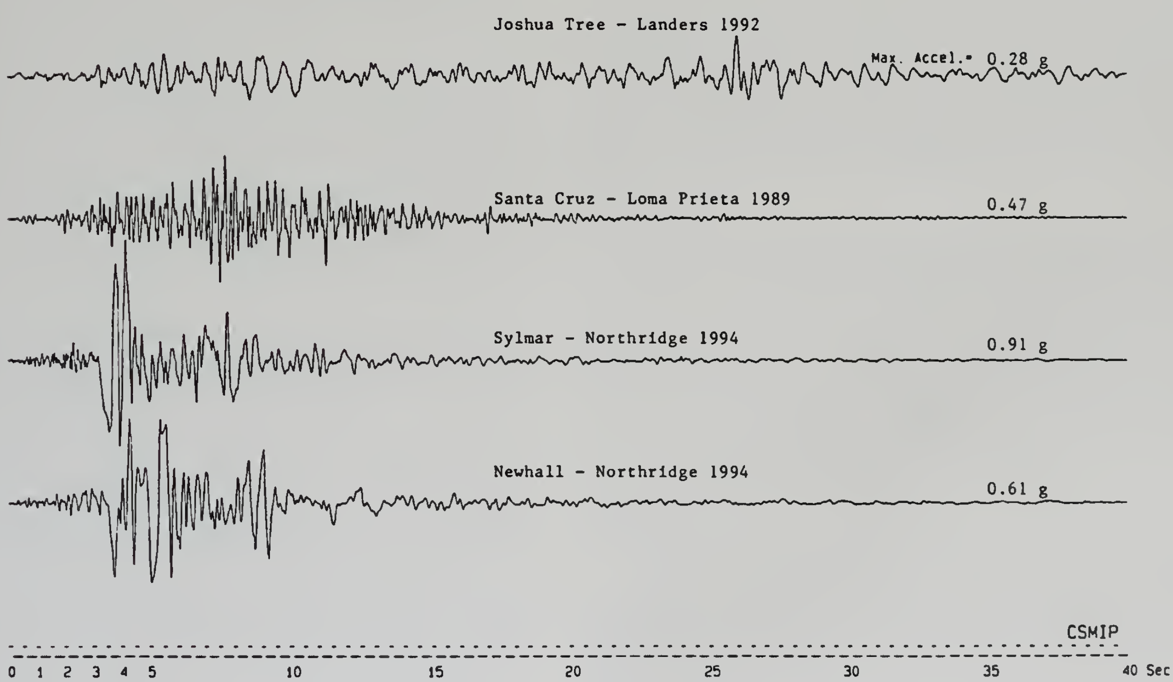


Figure 5. Duration of strong ground shaking. Accelerograms are from Joshua Tree for the 7.3 M Landers earthquake, Santa Cruz for the 7.1 M Loma Prieta earthquake, and Sylmar and Newhall for the 6.7 M Northridge earthquake. Stations are located at similar distances (10 - 20 km) from the fault.

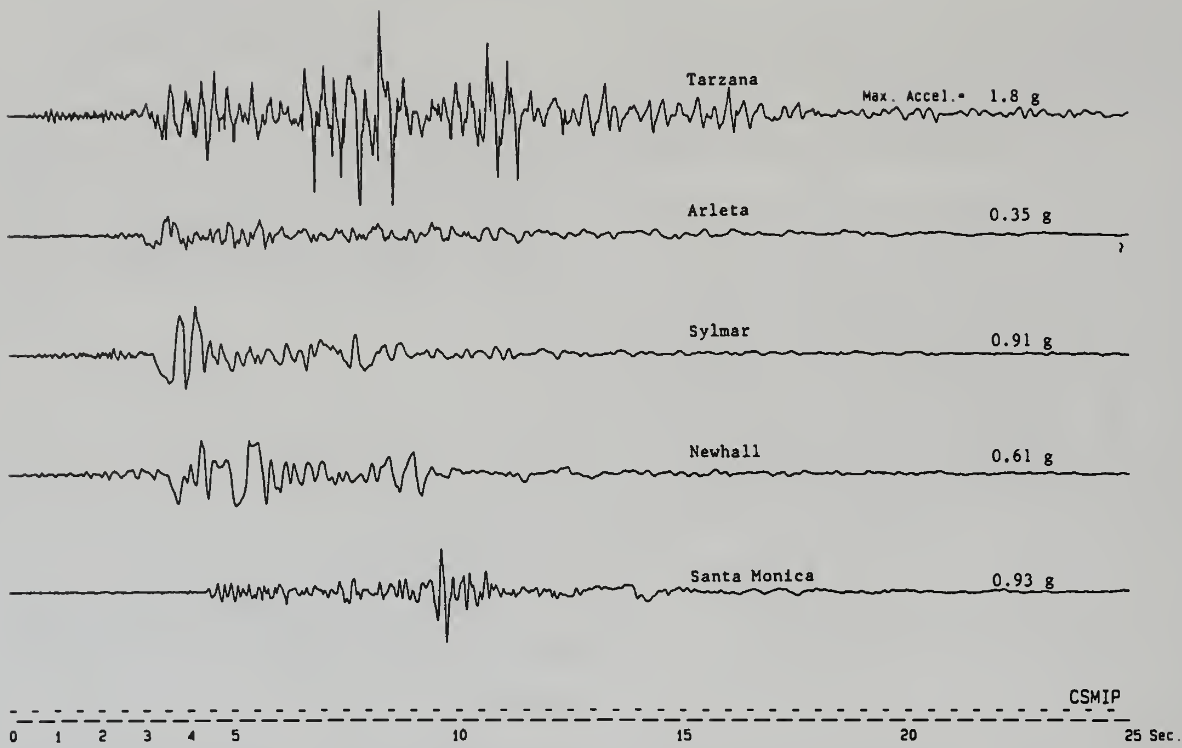


Figure 6. Comparison of acceleration waveforms at five ground-response stations within 25 km of the epicenter of the Northridge earthquake. Tarzana, Arleta, and Sylmar are in the San Fernando Valley. Newhall is located to the north of the Valley and Santa Monica is located to the south in the Los Angeles basin.

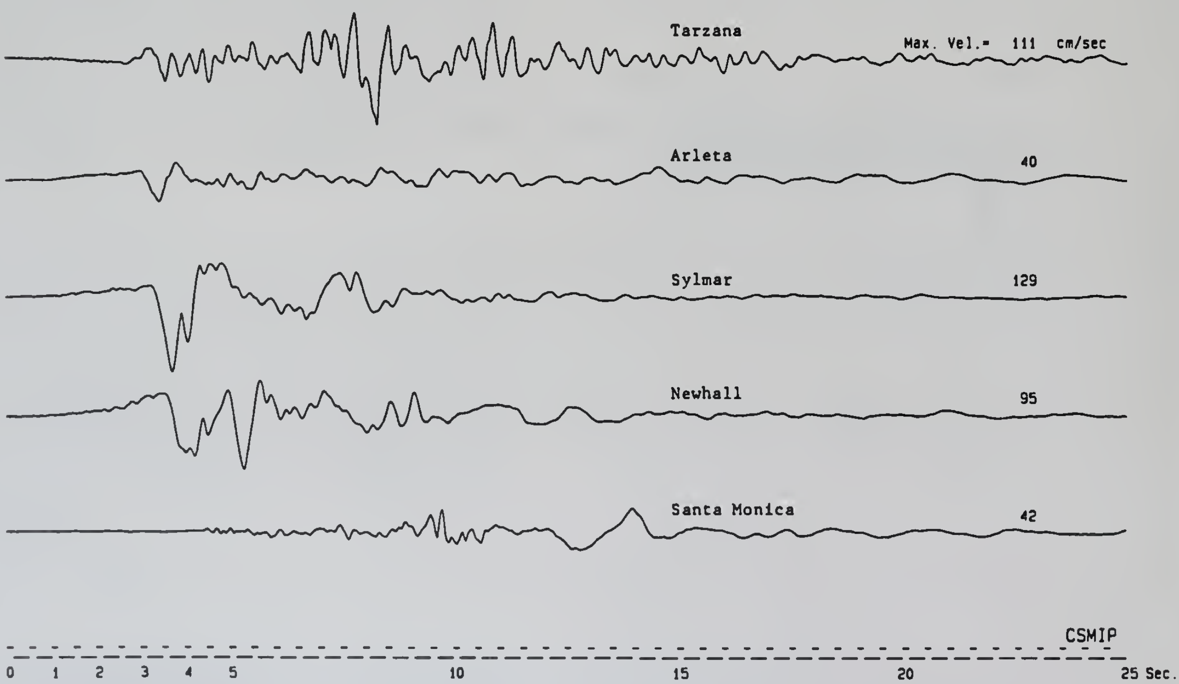


Figure 7. Comparison of velocity waveforms at the five ground-response stations considered in Figure 6.

tion near the county hospital in Sylmar was about 130 cm/sec and the peak velocity was about 170 cm/sec at the Los Angeles Department of Water and Power Rinaldi Receiving station (Lindvall Richter Benuska, 1994).

Tarzana

The record from the Tarzana ground-response station, about 5 km south of the epicenter, shows repeated accelerations over 1 g, for 7 to 8 seconds, with a maximum horizontal acceleration of about 1.8 g. All three components had accelerations over 1 g. Note that this station also had an isolated high-amplitude peak in the 1987 Whittier Narrows earthquake, though not in the largest Whittier aftershock nor several other events, including the 7.3 M Landers earthquake.

Only moderate structural damage was observed in the vicinity of this station. Structural types in the area are limited to 1-story and 2-story buildings. Figure 6 shows the instrument-corrected acceleration at Tarzana, and the velocity is shown in Figure 7. The peak velocity is over 100 cm/sec at Tarzana; velocities this high are also observed at the Sylmar and Rinaldi Receiving stations.

The station is located near the crest of a low (20 m) natural hill on the south side of the San Fernando Valley. The site is underlain by a variable thickness of colluvial soil (silty clay) estimated to be about 0.5 to 1.5 m in thickness. The soil is derived by in-place weathering of a soft claystone and siltstone of the Upper Modelo Formation which underlies the soil.

Additional accelerographs were deployed near the station after the Northridge earthquake and numerous aftershock records were obtained, some with peak acceleration as high as 0.25 g. The accelerations and response spectra at Tarzana and a nearby reference station are compared in Figure 8 for the largest aftershocks. The reference site is located about 120 m from the Tarzana station, off the gentle hill. For the largest aftershock (5.3 M) the stations have almost identical peak accelerations of about 0.25 g. In other words, no amplification of peak acceleration is observed in the shaking from the largest aftershock. For that event, the spectra for Tarzana and the reference site (Figure 8) are similar at short periods and long periods but show an amplification of 2 to 3 times near 0.2 seconds (5 Hz) at Tarzana. For the 4.4 M aftershock, the Tarzana peak acceleration was 0.12 g, three times that at the reference site (0.04 g). For this event, the Tarzana spectrum is nearly four times that of the reference site in the 3 to 5 Hz range, but now the Tarzana spectrum is also amplified at short periods, reflecting the amplified peak acceleration. Analysis of additional records is underway to investigate the stability of the spectral shape. These two stations document the large variability of strong ground motion possible over a distance of only 120 m and indicate the source of some of the scatter in peak accelerations in Figure 2.

The causes of the large motions at Tarzana are still under investigation. Darragh and others (1994j) reported that the Tarzana site amplified peak acceleration by a factor near two for many of the aftershocks. Spudich and others (1994) report a predominance of 2 to 6 Hz motion in weak motion recordings at Tarzana. Site characterization work has not established a cause for the large motions and long durations. A borehole was drilled to 30 m and logged by Fumal and others (1981), who report a shear-wave velocity in the claystone of about 400 m/sec. However, this borehole was drilled about 260 m west of the present SMIP station location so only the deeper portion of the borehole may be extrapolated laterally to beneath the station.

Arleta

The second closest SMIP ground-response station, approximately 10 km east of the epicenter, recorded a maximum horizontal acceleration of 0.35 g, but a higher vertical acceleration of 0.59 g (Figure 3). In Figures 6 and 7 the acceleration and velocity at this station are compared with Tarzana. Both stations are located within 10 km of the epicenter in the San Fernando Valley. Arleta recorded significantly lower maximum accelerations, velocities and displacements than at Tarzana; the maximum velocities and displacements are about one-third the values at Tarzana and several other stations. The reasons for these low values have not yet been determined, but may be due to non-linear soil behavior at the site or source radiation characteristics, among others.

Sylmar

The ground-response station in the parking lot of the County Hospital recorded a peak horizontal acceleration of 0.91 g and a peak vertical acceleration of 0.6 g. As shown in Figure 7 the maximum velocity is larger than at Tarzana. For reference, this station is approximately 6 km east of the I5/Hwy 14 interchange which collapsed and 16 km north-east of the epicenter.

Newhall

The Newhall station is located about 20 km north of the epicenter, in the direction of rupture propagation. This station recorded a maximum acceleration near 0.6 g on all three components; the north component is shown in Figure 6. As shown in Figure 7 the maximum velocity is near 100 cm/sec, similar to Tarzana. There are localized areas of significant damage to buildings in the Newhall-Santa Clarita area.

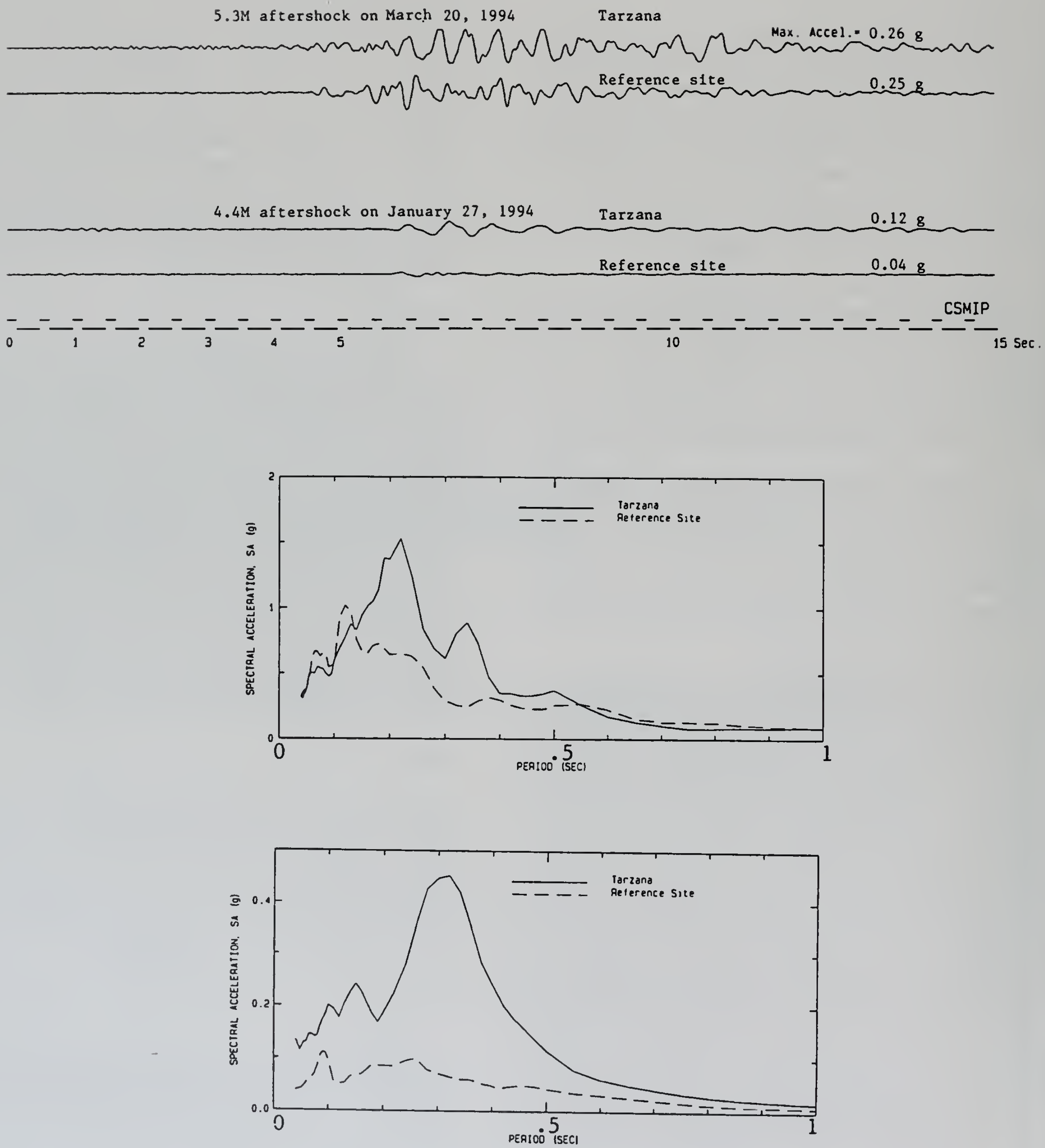


Figure 8. Comparison of accelerograms and spectra (5% damped) for the two largest Northridge aftershock records from the Tarzana SMIP station and a nearby reference site. The reference site is located off the hill and about 120 m from the Tarzana SMIP station. Peak accelerations of 0.26 g at Tarzana and 0.25 g at the reference site were recorded during the 5.3 M aftershock on March 20, 1994. Peak accelerations of 0.12 g at Tarzana and 0.04 g at the reference site were recorded during the 4.4 M aftershock on January 27, 1994.

Santa Monica

The ground-response station at Santa Monica City Hall recorded a peak horizontal acceleration of 0.93 g (Figure 6). This station is approximately 23 km south of the epicenter and about 11 km west of the section of the I-10 freeway that collapsed. There are many damaged buildings in the area. The velocity record in Figure 7 shows a peak velocity of over 40 cm/sec in the late-arriving energy near 15 seconds. This late arrival is also observed at several other stations in the Los Angeles basin.

SUMMARY

This paper has considered some aspects of the recorded and processed strong-motion data from the Northridge earthquake, concentrating on the variability of strong ground motion with distance and azimuth, and a discussion of the local ground-response at several stations. In this earthquake, distance and azimuth from the fault rupture surface along with site geology all had important effects on strong ground shaking. However, no clear trend in site amplification is apparent in contrast to the Loma Prieta earthquake which highlighted the effects of soft-soil response to strong ground motion. Additional study of the site response at Tarzana, Arleta, and other stations will increase the understanding of stiff-soil site response, where most of California's urban areas are located.

The large accelerations and velocities recorded during this earthquake, especially in the San Fernando Valley, are unprecedented and will lead to the revision of current attenuation relationships. Also, design criteria, assumptions, and analysis techniques for structures can be verified by analyzing these records in greater detail.

ACKNOWLEDGMENTS

The Strong Motion Instrumentation Program extends its appreciation to the individuals and organizations that have permitted and cooperated in the installation of strong-motion equipment on their property. The records presented herein were made possible through the efforts of many SMIP technicians who have installed, maintained, and recovered records at these stations.

REFERENCES

Cramer, C. and Darragh, R., 1994, Peak accelerations from the 1992 Landers and Big Bear, California earthquakes: Bulletin of the Seismological Society of America, v. 84, no. 3, p. 589-595.

Darragh, R., Cao, T., Cramer, C., Graizer, V., Huang M., and Shakal, A., 1994a-i, Processed CSMIP strong-motion records from the Northridge, California earthquake of January 17, 1994 — Release No. 1 through Release No. 9: California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 94-06 through 94-17.

Darragh, R., Shakal, A., Cao, T., Cramer C., and Graizer, V., 1994j, Outstanding features of the ground motion from the 1994 Northridge, California earthquake (abstract): Seismological Society of America, Program for Northridge Abstracts.

Fumal, T., Gibbs, J., and Roth, E., 1981, In-situ measurement of seismic velocity at 19 locations in the Los Angeles, California region: U.S. Geological Survey, Report No. OFR 81-399.

Joyner, W. and Boore, D., 1988, Measurement, characterization, and prediction of strong ground motion: Proceedings of Earthquake Engineering and Soil Dynamics II Geotechnical Division/ American Society of Civil Engineers, Park City, Utah, June 27-30, 1988, p. 1-60.

Lindvall Richter Benuska, 1994, Processed LADWP power system strong-motion records from the Northridge, California earthquake of January 17, 1994: LRB No. 007-027, June 23, 1994. 165 p.

Porcella, R., Etheredge, E., Maley, R., and Acosta, A., 1994, Accelerograms recorded at USGS National Strong-Motion Network stations during the Ms=6.6 Northridge, California, earthquake of January 17, 1994: U.S. Geological Survey, Report No. OFR 94-141, 100 p.

Shakal, A., Huang, M., and Cao, T., 1988, The Whittier Narrows, California earthquake of October 1, 1987 — CSMIP strong motion data: Earthquake Spectra, v. 4, p. 75-100.

Shakal, A., DeLisle, M., Reichle, M., and Darragh, R., 1990, Strong ground shaking from the Loma Prieta earthquake of 17 October 1989, its relation to near surface geology in the Oakland area, *in* McNutt, S. and Sydnor, R., eds., The Loma Prieta (Santa Cruz Mountains), California, earthquake of 17 October 1989: California Department of Conservation, Division of Mines and Geology, Special Publication 104, p. 29-46.

Shakal, A., Huang, M., Darragh, R., Cao, T., Sherburne, R., Malhotra, P., Cramer, C., Sydnor, R., Graizer, V., Maldonado, G., Petersen, C., and Wampole. J., 1994a, CSMIP strong-motion records from the Northridge, California earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 94-07, 308 p.

Shakal, A., Huang, M., and Darragh, R., 1994b, Some implications of strong-motion records from the 1994 Northridge Earthquake: Proceedings of SMIP94 Seminar on Seismological and Engineering Implications of Recent Strong Motion Data, California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, p. 1-20.

Spudich P., Harlow, D., Lee, W., and White, R., 1994, Strong site effects observed at the Tarzana accelerograph site using aftershocks of the 1994 Northridge, California earthquake —implications for microzonation (abstract): Seismological Society of America, Program for Northridge Abstracts.

Trifunac, M., Todorovska, M., and Ivanovic, S., 1994, A note on distribution of uncorrected peak ground accelerations during the Northridge, California, earthquake of 17 January 1994: Soil Dynamics and Earthquake Engineering, v. 13, no. 3, p. 187-196.

Barrows, A.G., Irvine, P.J., and Tan, S.S., 1995, Geologic surface effects triggered by the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 65-88.

GEOLOGIC SURFACE EFFECTS TRIGGERED BY THE NORTHRIDGE EARTHQUAKE

by

Allan G. Barrows[1], Pamela J. Irvine[1], and Siang S. Tan[1]

INTRODUCTION

Earthquakes as large as the Northridge event tend to generate an abundance of features that disrupt the land surface in diverse ways. Such features, produced by strong earthquake shaking, are called geologic surface effects. Landslides, rockfalls, disrupted or "tossed" soil along ridgetops, assorted ground cracks, and sand boils and ejected water due to liquefaction are all properly labelled "geologic surface effects." Ground-failure phenomena in artificially placed fill materials are also discussed in the following account, although, strictly speaking, these are "geotechnical" rather than "geologic" effects because they do not occur in natural ground.

Not included in the discussion are cracks and fissures due to surface rupture along faults, where ground along the trace of a fault is displaced, or where beds of inclined strata slip past each other and warp or break the surface. The chapter on the search for fault rupture discusses these topics. Neither does the term "geologic surface effects" refer to structural failure or damage to buildings, bridges, highways, and other public and private structures.

The most plentiful and widespread surface effects triggered by the Northridge earthquake are landslides of all types. The great majority of slope failures triggered by the earthquake are shallow rock, soil, or debris falls and slides that occurred over a broad region extending in all directions from the epicenter. Nevertheless, movement of large masses of earth and rock in the form of slumps or rotational and translational landslides probably caused more damage to the works of man than did all of the thousands of rockfalls and rock slides, even taking into account the innumerable slides from roadcuts in the region.

The brief but extremely violent shaking during the earthquake that triggered so many rockfalls and debris slides also created distinctive, locally striking, effects concentrated along the tops of many narrow ridges in the region. Highly disrupted soil caps or "shattered ridge tops," as they are called, which resemble freshly plowed ground, developed along those ridges where suitable geologic and topographic conditions occurred in areas subjected to intense shaking.

The process of liquefaction, initiated during the relatively short period of intense shaking, left signs of its occurrence at widely scattered localities, some of which are at surprising distances, as much as 38 miles (60 km), from the epicenter. Even though key evidence of liquefaction, such as sand boils or fringes of ejected water and sand mixtures bordering fissures, was scattered over a broad region, the actual damage due primarily to liquefaction was concentrated at those localities where artificial fill experienced failure. An additional manifestation of liquefaction, lateral spreading, was noted at numerous localities in the earthquake area, especially along the edges of stream banks, berms, and fill embankments.

[1]California Department of Conservation, Division of Mines and Geology, Southern California Regional Office, Los Angeles, California

A particularly damaging surface effect of the Northridge earthquake, seen in hundreds of places, was cracking or ground failure of varying severity that resulted from differential settlement in artificial fill. Although commonly considered an engineering topic, this form of ground failure is discussed herein because it affected many areas where land, graded decades ago, includes inadequately prepared fill materials too weak to resist settlement problems.

Observations and conclusions from detailed studies by Division geologists of the earthquake effects and related damage in the Sherman Oaks area of the Santa Monica Mountains (Tan, 1995) and ground failure in Simi Valley (Barrows, Tan, and Irvine, 1994) are summarized in separate sections in this chapter as well.

LANDSLIDES AND ROCKFALLS

Types of Landslides

Landslides are often classified according to the type of motion connected with their origin – falls, slides, and flows. Surficial failures only a few feet thick, most of which involved only loose soil and fragments of weathered bedrock, were by far the most common slope failures generated by the earthquake. The steepest slopes produced rockfalls, soil falls, and avalanches. Less steep slopes produced debris slides and mobilized rubble in talus cones and aprons of rock fragments beneath cliffs. Concentration of slope failures within specific lithologic units or beds was also common. For example, Pico Formation sandstone and conglomerate beds in Pico Canyon generated abundant rockfalls (Photo 1).

Photo 1. Rockfall from massive sandstone beds in marine Pico Formation along Pico Canyon Road. Photo by S.S. Tan, 1/22/94.

Although much less common than rockfalls and debris slides, portions of large, massive or coherent landslides were reactivated within elevated regions within 22 miles (35 km) of the epicenter, especially the Santa Monica Mountains, the Santa Susana Mountains, and north of the Santa Clara River between Castaic Junction and Piru.

Geologic and Geomorphic Setting

The distribution of landslides triggered by the earthquake is a reflection of shaking intensity. Equally, if not more importantly, geologic and geomorphic factors within the affected area control the concentrations and types of slope failures triggered by the earthquake.

The earthquake area lies within the Transverse Ranges geologic province, which has a structural "grain" dominated by an east-west alignment of major fold axes and faults. As a consequence, the main west-trending mountain ridges generally have steep north- or south-facing slopes. Ground motion during the earthquake was generally stronger in a north-south direction, as evidenced by strong-motion records (Shakal and others, 1994) and observations that greater damage occurred to east-west-trending block walls and heavy objects, oriented perpendicular to the north-south shaking direction, were more likely to be upset or overturned. Accordingly, when pronounced directional shaking was superimposed upon terrain with primarily north- or south-facing slopes concentrations of slope failures readily formed on these slopes.

The lithology of each of the geologic units exposed in the area contributes significantly to the formation of slope failures and influences the distribution of failure types. The diverse rocks within the elevated terrain affected by the earthquake include: very old crystalline gneisses and plutonic rocks in the San Gabriel Mountains; a varied assemblage of marine and nonmarine sedimentary strata and interbedded volcanic rocks of Cretaceous through Tertiary age that comprise the Santa

Susana Mountains, Simi Hills, and the Santa Monica Mountains; and, in much of the deeply dissected foothill terrain along the northern margin of the San Fernando Valley and the Santa Clarita region, tilted and deformed Quaternary beds of fluviatile and lacustrine origin. This assortment of rock types has experienced a very complex geologic history that has produced a complex pattern of faults and folds. Intense deformation of the rocks in recent geologic time has elevated masses of inherently weak rocks, such as siltstone, exposing them to the forces of erosion. It has also fractured and jointed and, thus, weakened rocks along fault zones and within tight folds. These things contribute, as well, to an increased tendency toward slope failure.

Regional Landslide Setting

A great number of landslides of many kinds, as well as abundant evidence of slope failure, such as debris-flow or soil-slip scars, were present within the area prior to the earthquake. Several geologic units, which happen to be widely distributed in the region, are readily susceptible to deep-seated landsliding. For example, the Miocene Modelo Formation of marine origin, which includes fine to coarse sandstone and conglomerate beds and abundant, thin-bedded, siliceous silty shale layers, contains thousands of landslides. Also extremely susceptible to large-scale mass movement are the silty and clayey beds of the Pliocene Pico Formation. Mapping for purposes of assessing landslide susceptibility within the region has repeatedly documented these conditions (see Treiman, 1986, 1987; Barrows, 1986; Irvine, 1990). Surficial slope failures, such as debris flows, mudflows, and soil slips are common and, frequently, very troublesome during seasons when intense rainstorm activity dumps large amounts of water on vulnerable slopes. Such was the case when slopes throughout the earthquake area were heavily damaged by rainstorm-triggered soil-slip/debris flows and mudflows in 1969, 1978, and 1980 (Campbell, 1975; Weber and others, 1978; Weber, 1980). The high landslide susceptibility of much of the terrain, as well as its vulnerability to rapid forms of shallow failure (mudflows), are well-documented conditions that existed within the area when the earthquake struck. In other words, the earthquake simply compressed in time landslides that would be likely to occur under climatic conditions, although the proportions of the various kinds of slides would probably be different.

Distribution of Landslides Triggered by the Northridge earthquake

Landslides and other surface geologic effects of the earthquake were scattered over an area covering about 2880 square miles (7500 km^2) (Figure 1). Maps of the distribution and location of more than 11,000 rockfalls and other landslides triggered by the earthquake have been complied by Ed Harp and Randall Jibson of the U.S. Geological Survey (Harp and Jibson, 1995). This vast region, primarily due to the high intensity of shaking, is more than twice the size of the area affected by landslides in the M_w 6.7 San Fernando earthquake of 9 February 1971, which was approximately 1350 square miles (3500 km^2) according to Keefer (1984, Figure 1). In fact, the area of rockfalls and landslides from the M_w 6.7 Northridge earthquake even exceeds the area affected by the much larger, M_w 7.3 Landers earthquake of 28 June 1992, which was 2,700 square miles (7,000 km^2) as reported by Barrows (1993, p.17).

The greatest distance from the epicenter that landslide features were observed is 45 miles (72 km), where small cones of gravel collected as talus in roadcuts along State Highway 33 near Wheeler Springs in Ventura County (Figure 1, locality 1). North of the epicenter, unequivocal evidence of rockfalls from roadcuts was observed near Gorman (Figure 1, locality 2), 43 miles (69 km) from the epicenter (Randall Jibson, personal communication, 1994). To the south, rockfalls from seacliffs were reported along the Palos Verdes Peninsula 38 miles (61 km) from the epicenter.

The maximum distance for the reactivation of preexisting landslides is about 22 miles (35 km) from the epicenter (Figure 1, locality 12). In contrast, the maximum distance for coherent landslide movement triggered by the 1971 San Fernando earthquake was 12.5 miles (20 km), according to Keefer (1984, Figure 2B).

Santa Susana Mountains

The greatest concentrations of rock and soil falls, avalanches, and debris slides occurred in the tightly folded, steeply dipping, silty and sandy beds of the Towsley and Pico formations in the Pico and Towsley canyon areas within the Santa Susana Mountains (Figure 1, locality 3). In many places, more than half of the surface material along the canyon walls fell or slid down in shallow failures. Vast quantities of dust visible above the mountainous regions were created by the sliding not only during the mainshock but repeatedly during larger aftershocks.

The susceptibility to rockfalls, specifically along the cliffs of Pico Formation that form the north wall of Pico Canyon, was emphasized by Treiman (1986, Plate 2A2). Indeed, steep to vertical cliffs in sandstone and conglomerate beds of the Pico Formation were the source of numerous large rockfalls (Photo 1).

At the eastern end of the Santa Susana Mountains, on Oat Mountain, large, complex landslides are extremely common in rocks of the Modelo Formation, especially in

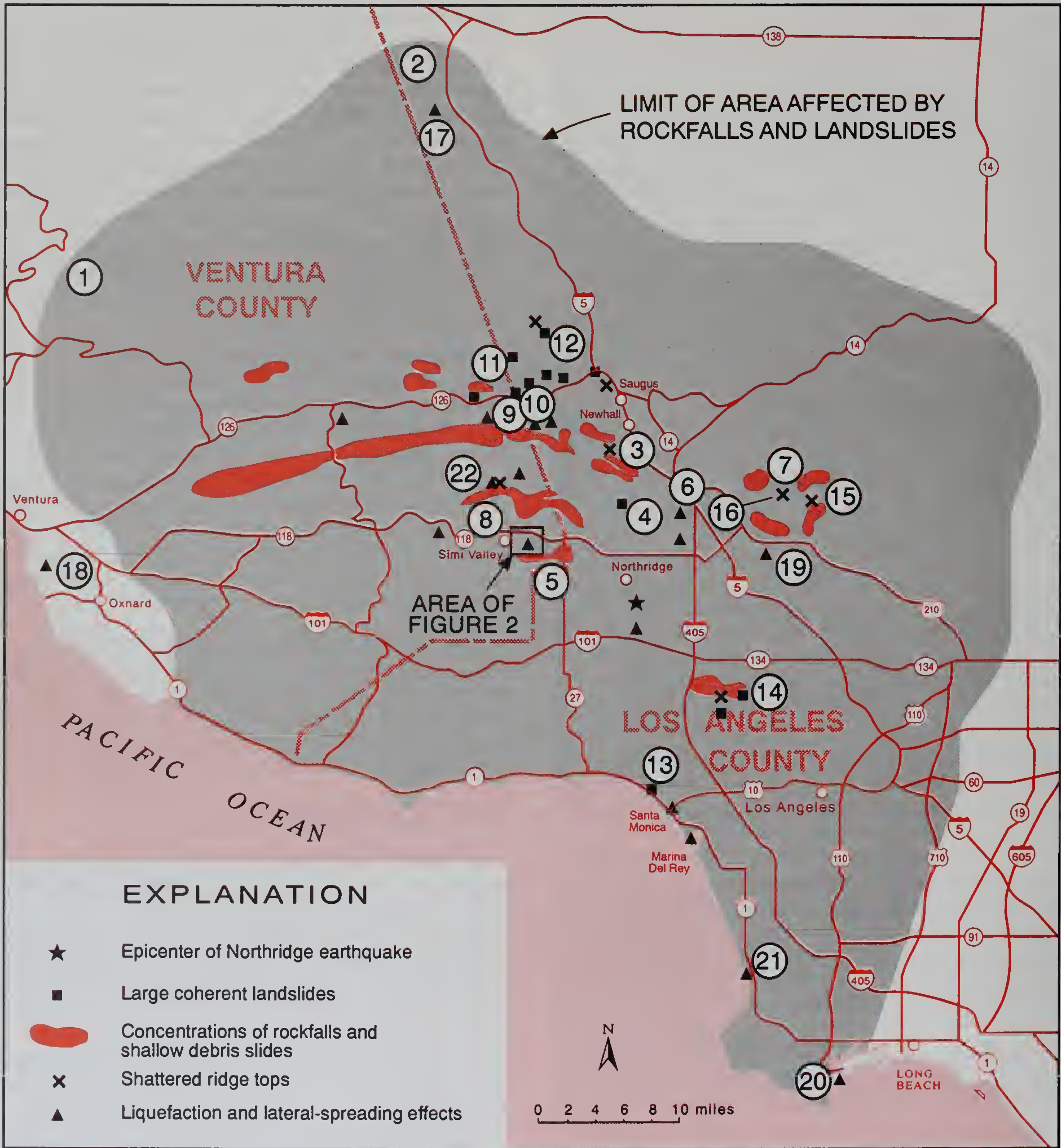


Figure 1. Distribution of selected geologic surface effects from the Northridge earthquake. Map also shows limit of area affected by rockfalls and landslides and numbered localities discussed in the text.

the vicinity of Mission Point (Barrows and others, 1975b, Plate 2; Saul, 1979, Plate 1). During the earthquake, portions of many pre-existing landslides were reactivated and several new slumps developed, as well, on the slopes above Granada Hills. In the Aliso Canyon Oil Field on Oat Mountain (Photo 2) landslides damaged oil facilities and fill settlement disrupted access roads (Figure 1, locality 4).

Santa Susana Pass Road was closed where it enters the southeastern corner of Simi Valley due to numerous rockfalls, primarily from north-facing roadcuts (Photo 3) in blocky and jointed, Cretaceous marine sandstone of the Chatsworth Formation (Figure 1, locality 5).

Photo 2. View south from top of Oat Mountain toward oil well in Aliso Canyon Oil Field sitting on cut pad in older landslide. To right of oil well are fresh headscarps and curved cracks from Northridge earthquake-triggered enlargement of pre-existing landslide. Photo by S.S. Tan, 1/26/94.

Photo 3. Rockfall onto Santa Susana Pass Road just west of the pass from north-facing roadcut in massive sandstone of the Cretaceous Chatsworth Formation. Photo by P.J. Irvine, 1/19/94.

San Gabriel Mountains

In the foothills north of San Fernando, landslides were localized primarily along siltstone and fine-grained sandstone beds in the Towsley and Pico formations as they were during the San Fernando earthquake (Morton, 1975, Photo 2). Shallow soil falls and debris slides (Photo 4) also occurred on many of the same slopes within the Modelo Formation that failed in 1971. In fact, near San Fernando Pass (Figure 1, locality 6), a rockfall toppled on top of debris that dropped in 1971 (compare Photo 5 with Morton, 1975, Photo 3). Rockfall and rock-slide activity was widespread within the jointed and fractured igneous and metamorphic rocks that comprise the elevated and deeply dissected portions of the San Gabriel Mountains. Roads, such as the Angeles Forest Highway, within the mountains

Photo 4. Very shallow soil falls and debris slides on south-facing slopes in Modelo Formation sandstone at the mouth of Lopez Canyon. The trace of the Tujunga Segment of the San Fernando Fault Zone lies at the base of the slope on the right. Photo by A.G. Barrows, 1/18/94.

were blocked in numerous places by rockfalls and debris slides.

The collapse of freeway overpass structures in San Fernando Pass resulted in enormous traffic-congestion problems for commuters attempting to reach the Los Angeles area from the Santa Clarita and Antelope Valley areas. One alternate route from Antelope Valley, Little Tujunga Road, was blocked for several days by rockfall and landslide debris. Although several miles of this road traverse very rugged terrain with large, steep roadcuts, rockfalls and debris slides were only prevalent along stretches of the road that are close to strands of the San Gabriel Fault Zone (Photo 6; Figure 1, locality 7). The concentration of slope failures primarily along the

Photo 5. Rockfall from west-facing cliff in Pico Formation sandstone at south end of San Fernando Pass. Light-colored debris fell upon rockfall deposit that resulted from larger landslide triggered by 1971 San Fernando earthquake. Photo by S.S. Tan, 1/22/94.

Photo 6. Large rockslides along Little Tujunga Road that originated in shattered granitic and metamorphic rocks directly on trace of San Gabriel Fault one mile (1.6 km) west of Dillon Divide in the San Gabriel Mountains. Photo by A. G. Barrows, 1/20/94.

fault traces is due to a combination of factors. Igneous and metamorphic rocks close to the fault are densely sheared and fractured because of innumerable movements along this fault zone. In addition, reconnaissance of the region traversed by the San Gabriel Fault immediately after the earthquake, led to the observation that surface effects were substantially more abundant southwest of the fault zone than in the region northeast of the trace. Apparently, the fault plane acted as a reflector of seismic energy, which resulted in effects clustering near the fault. Consistent with this assertion is the evidence seen near Bouquet Junction, several miles northwest of Little Tujunga Road, of a concentration of effects close to the trace of the San Gabriel Fault that included ground cracks, aligned with the strike of the fault, with as much as 3 cm of right-lateral displacement. Again, this is not a manifestation of actual "fault movement" but is likely due to focusing of shaking in the vicinity of the fault where it juxtaposes different geologic units with, very likely, contrasting physical properties.

North of Simi Valley

Tapo Canyon cuts through the mountains that border Simi Valley on the north and defines the boundary between the Santa Susana Mountains on the east and Big Mountain on the west. About 2.5 miles (4.0 km) north of the Simi Valley Civic Center, the prominent, south-facing, barren cliffs, locally known as "White Face," along Big Mountain are composed of brilliant white beds of diatomaceous shale and siltstone of the marine Modelo Formation underlain by nonmarine sandstone and claystone beds of the Sespe Formation (Figure 1, locality 8). During the earthquake and several of the large aftershocks abundant rockfalls and rock slides were shaken loose from the cliffs. Accompanying the rock slides were dense clouds of dust (Photo 7). During the months immediately following the

Photo 7. View northward toward the cliffs of "White Face" on Big Mountain from the City of Simi Valley Civic Center. Clouds of dust and rockfalls resulted from a 5.0 magnitude aftershock centered 5 miles east of Simi Valley on January 19, 1994. Photo by P.J. Irvine.

Photo 8. Rockfall from north-facing cliffs in Tapo Canyon, north of Simi Valley. Photo by S.S. Tan 2/1/94.

Photo 9. View west along headscarp of immense landslide west of Del Valle Oil Field 1.2 miles (2 km) north of Highway 126 near the Ventura-Los Angeles County line. Note person for scale on left. Photo by S.S. Tan, 3/2/94.

Northridge earthquake, an unusually high incidence of Valley Fever was reported in Simi Valley, Thousand Oaks, and elsewhere in eastern and southern Ventura County. It has been suggested that rock slides generated during the mainshock and aftershocks caused Valley Fever fungus spores, which occur in local soils, to become airborne. Dust clouds containing the spores were transported by winds southwestward across Simi Valley and eastern Ventura County. The outbreak of Valley Fever in Ventura and western Los Angeles County is being investigated by medical personnel from the Centers for Disease Control and Prevention in Atlanta to confirm the connection between the earthquake and the surge in Valley Fever cases (Dr. Richard Spiegel, personal communication, 1994).

Photo 10. Graben and multiple back-tilted scarps in the western portion of the Del Valle landslide. View toward southwest. Person for scale at left. Photo by A.G. Barrows, 1/31/94.

Not only were rockfalls common on south-facing slopes, such as White Face, but they also developed abundantly along north-facing slopes in the Tapo Canyon-Big Mountain region as well (Photo 8). The location of landslides in this area reflects the strong north-south component to the shaking. Additional manifestations of the directional aspect to the ground motion were observed near the northern mouth of Tapo Canyon, just south of the Santa Clara River, two miles (3.2 km) west of the Ventura County line. Jerome Treiman (written communication, 1994) reported that ground cracks were widespread within the terrace deposits of Tapo Creek on the Las Brisas orchard property (Figure 1, locality 9). Treiman ascribed the ground failure, which consisted of cracks, scarps, and graben, to lateral spreading or lurching. He did not observe sand boils nor could he otherwise confirm that liquefaction had occurred, although the ranch foreman reported that the land was heavily irrigated prior to the earthquake and the ground was presumably saturated.

North of the Santa Clara River

Concentrated in the region between Castaic Junction and Piru, predominantly within the Val Verde 7.5-minute quadrangle, are many of the most prominent geologic surface effects produced by the earthquake. Although ground-failure features in Potrero Canyon, south of the Santa Clara River, discussed elsewhere in this volume, have received much attention, truly the most spectacular surface geologic effects of the Northridge earthquake are several immense landslides north of the river.

As depicted on geologic maps of the Val Verde area (Winterer and Durham, 1962; Barrows, 1986; Dibblee, 1993), complexes of large landslides are very abundant in terrain underlain by the siltstone and fine-grained sandstone member of the Pliocene marine Pico Formation. Coincidently, both the Ramona and Del Valle oil fields, which lie along the Los Angeles-Ventura County border north and south of San Martinez Grande Canyon, respectively, are also situated within Pico Formation siltstone units exposed along the axes of large anticlinal folds. The largest landslide triggered by the Northridge earthquake straddles the county line 1.2 miles (2 km) north of Highway 126, south of San Martinez Grande Canyon, and west of the Del Valle oil field (Figure 1, locality 10). This huge rotational landslide was produced by reactivation of a pre-existing massive landslide (triggered by a pre-historic earthquake?) along with substantial enlargement by headward migration toward and, locally, beyond, the top of a ridge on the north. The headscarp is at least 0.5 mile (0.8 km) long and as much as 80 feet (24 m) high (Photo 9). Disrupted and fissured ground covers more than 40 acres. The total volume of mobilized material probably exceeds 5 million cubic yards (3.8 million m^3). In the upper portion of the landslide, dramatic graben and back-tilted blocks developed parallel to the headscarp (Photo 10). On the western half of the landslide numerous cracks and fissures developed at right angles to the primary transverse cracks. Within this jumbled terrain, the siltstone and fine-grained sandstone beds of the Pico Formation were literally pulverized (Photo 11) during what must have been extremely violent shaking in the headscarp area.

Photo 11. Fine-grained sandstone of the Pico Formation was thoroughly pulverized by extremely intense shaking along the top of the ridge at the head of the Del Valle landslide just west of the Ventura-Los Angeles County line. Photo by A.G. Barrows, 1/31/94.

Photo 12. Large slump-type landslide on a dip slope in fine-grained Pico Formation sandstone beds along the ridge north of San Martinez Grande Canyon. Slide damaged oil facilities in the Ramona Oil Field. Photo by S.S. Tan, 3/2/94.

Perhaps a dozen other very large landslides, mostly slumps, developed on south-facing dip slopes in Pico Formation siltstone in the Val Verde and Piru quadrangles. In the Ramona oil field, north of San Martinez Grande Canyon large landslides (Photo 12) damaged oil wells, tanks, and access roads (Figure 1, locality 11). Several large slumps, visible from Highway 126, developed along the ridge top about one mile (1.6 km) north of the highway and two miles west of the Los Angeles County line. The farthest north that a very large landslide was triggered by the earthquake, 22 miles (35 km) from the epicenter, is just west of Loma Verde near the northern boundary of the Val Verde quadrangle (Figure 1, locality 12).

Santa Monica Mountains

Among all the elevated regions strongly affected by the earthquake, the Santa Monica Mountains suffered the greatest amount of damage to structures and utility lines. This is a consequence of several factors: the proximity to the epicenter, the quantity and age of structures built on steep slopes, the lithology and structure of the geologic units underlying the terrain, and the occurrence of pre-existing landslide deposits. Although slope failures were most abundant in Sherman Oaks (discussed in detail below), landslides also occurred in the northern hillside areas from Universal City to Woodland Hills. The most common manifestation of the earthquake in this region was the rockfalls and slides that fell onto roads from platy shale layers of the Modelo Formation exposed in steep cuts (Photo 13). Many of the roads along canyon walls were put in place more than 60 years ago and the cuts in the weak and fractured shale are deeply weathered. The ground motion from the Northridge earthquake was much stronger than the roadcuts had ever been subjected to and abundant failures resulted. Shallow soil falls and debris slides, so common elsewhere in the region, were also common on sparsely vegetated south-facing slopes in Modelo Formation on the northern side of the Santa Monica Mountains (Photo 14).

South of the crest of the Santa Monica Mountains, slope failures were very rare. One notable exception to this observation is the locally spectacular bluff failures that occurred in Pacific Palisades along

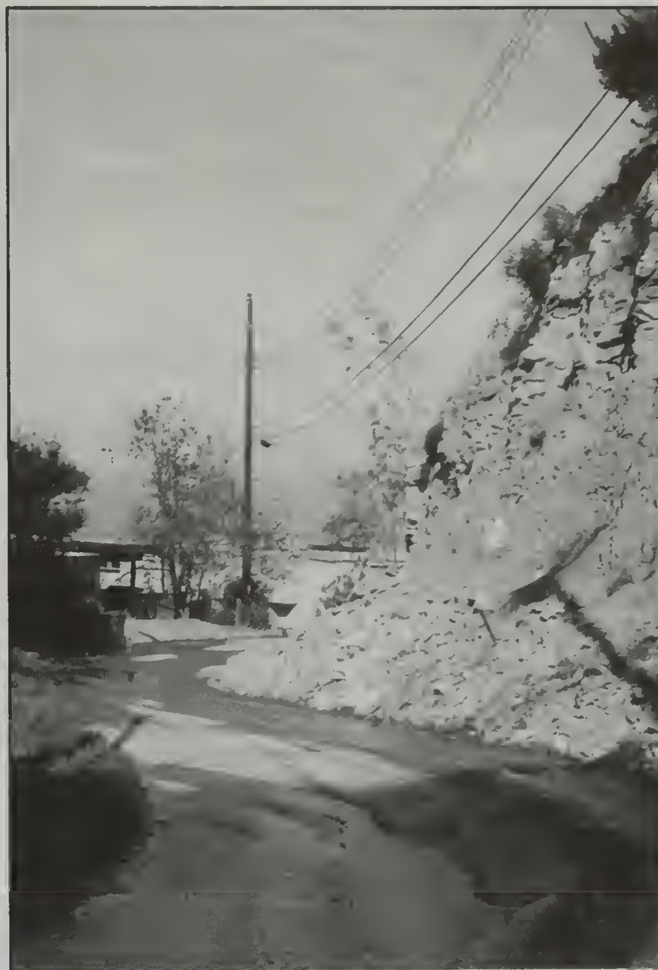


Photo 13. Piles of debris from earthquake-triggered rockfalls from roadcut in north-dipping platy shale and siltstone layers of the Modelo Formation on Oakfield Ridge Drive, Sherman Oaks, in the Santa Monica Mountains. Water on road is from broken water-pipe service connections beneath pavement. Photo by A.G. Barrows, 1/19/94.

Photo 14. Very shallow soil falls and debris slides on south-facing slopes descending from ridge traversed by Beverly Ridge Drive, Sherman Oaks, Santa Monica Mountains. Photo by S.S. Tan, 1/19/94.

Pacific Coast Highway (Figure 1, locality 13). The collapse of bluffs damaged or destroyed several homes and caused the closure of the highway between Chautauqua Boulevard and Temescal Canyon Road for several days. Additional failures are likely, perhaps during the next rainy season, where brittle blufftop terrace deposits, which are very susceptible to slumping, developed cracks from the strong shaking (Photo 15).

EARTHQUAKE EFFECTS AND GEOLOGIC FACTORS IN THE SHERMAN OAKS AREA

Extensive, locally catastrophic, earthquake-related damage to man-made structures, slope movement, fissuring of the ground, and cracking of artificial fill strongly affected the northern portion of the Santa Monica Mountains in Sherman Oaks. Surface effects were most common and damage was most severe between Coldwater Canyon Avenue on the east, the San Diego Freeway on the west, and north of Mulholland Drive. The observations, summarized in this section, resulted from an investigation conducted by Tan (1995) of Northridge earthquake effects in the Sherman Oaks area, combined with a study of preexisting landslides and regional landslide susceptibility.

Photo 15. Earthquake-generated extensional cracks along the top of bluffs in old terrace deposits in the Palisades Park, Pacific Palisades, just east of Temescal Canyon. Photo by S.S. Tan, 1/20/94.

The factors that contributed to plentiful damage, slope failure, and ground-failure problems include:

- Lithology. All of the earthquake-damaged hillside areas in Sherman Oaks are underlain by weak bedrock that consists of broken-up, thin-bedded, moderately to steeply north-dipping (inclined), intensively jointed siltstone, platy shale, and interbedded sandstone of the marine Modelo Formation. Most of the structural damage not associated with actual ground failure due to landsliding or fill disruption was localized within those areas underlain by the "Tud" or "unnamed shale" (upper part of the Modelo Formation) unit as depicted by Dibblee (1991). Rocks of the same unit underlie the Cedar Hill Nursery in nearby Tarzana, where extremely strong ground motion (maximum 1.82 g horizontal and 1.18 g vertical) was recorded (Shakal and others, 1994, p. 43).
- Dip slopes. Where the slant of the land surface generally coincides with the angle of inclination (dip) of the layering in underlying rock strata a potential for unstable slopes exists. This is because the orientation (attitude) of the bedding planes in the bedrock makes it easy for slippage to occur wherever downslope support is removed by erosion or grading activities. Evidence that slippage did occur along bedding planes on dip slopes was observed in many places (Photo 16). The single most catastrophic block-glide landslide due to slippage on a dip slope in Modelo Formation shale occurred on Alomar Drive south of Stoneridge Place destroying many houses (Figure 1, locality 14).

Photo 16. Crack across unpaved portion of Oakfield Ridge Drive, Sherman Oaks, in the Santa Monica Mountains, that opened up along the strike of the platy shale beds exposed in the roadcut. Bedding-plane slippage on a northward-facing dip slope caused the cracking. Photo by S.S. Tan, 1/19/94.

- Topography and ridgetop amplification. Earthquake damage on ridges underlain by weak bedrock was concentrated: along the very tops of ridges and hills that are typically narrower than 300 feet; on tops of ridges flanked by slopes steeper than 2.5:1 (40% slope); and on the steep sides of ridges that are higher than 100 feet above the base of the slope. Although, as noted above, structural damage was concentrated in those parts of the mountains underlain by platy shale beds of the Modelo Formation, an additional factor appears to have also played a strong role in the localization of structural damage. Even though no ground failure was observed, severe, locally catastrophic, structural damage occurred along the tops of linear ridges, such as those traversed by Beverly Ridge Drive and Coty Road due to the amplification or focusing of seismic energy. Major damage to structures located at the northernmost ends of many of these ridges was also very common.
- Old landslide headscarps and deposits. Ground cracks, fissures, and heavy damage to structures and utility lines were concentrated along headscarps and nearby upper portions of pre-existing landslides, particularly where slopes are steeper than 2.5:1 or the old landslides rest on dip slopes. Conversely, within the gentler slope areas of large landslides, beyond the immediate headscarp portion, earthquake effects were scarce.
- Damaged fill materials. The most abundant fissures and other ground cracks occurred in poorly engineered road fill, particularly along Mulholland Drive. Ground failure beneath streets and residential lots developed in many places where problems with settlement and downslope creep had been observed by residents prior to the earthquake.
- Joint patterns. A regional pattern of joints may have also contributed to increased damage along ridgetops, especially where the trend of the joints is parallel to linear ridges.

EARTHQUAKE EFFECTS AND GROUND FAILURE IN SIMI VALLEY

Within the City of Simi Valley, earthquake damage was extensive to buildings, streets, block walls, utilities, and drainage facilities. Although most of the damage was directly attributable to intense ground motion and strong shaking, in some parts of Simi Valley, especially in the southeastern quadrant near Arroyo Simi, considerable damage was associated with aspects of local ground failure, primarily fissuring and differential settlement. In order to make decisions about rebuilding of damaged public and private property, the City of Simi Valley requested technical assistance from the California Department of Conservation, Division of Mines and Geology. As a result of an agreement between the City and the State, Division geologists investigated surface effects such as cracks, fissures, evidence of ejection of water and fine sand and associated damage to pavements and other improvements. A report and a map depicting areas of prominent surface geologic effects superimposed upon the boundaries of the pre-development channel morphology of Arroyo Simi resulted from the study (Barrows and others, 1994).

The study focused on five subareas (see localities on Figure 2) where surface effects were most conspicuous:

- Vicinity of Christine Avenue and Hope Street (Figure 2, locality 1). A single, west-trending, steplike crack with vertical offset between 12 and 18 inches (30-45 cm) disrupted Christine Avenue. Bordering Hope Street, several houses were seriously damaged and some were destroyed because of broken foundations and tilting of walls due to cracking of the ground that accompanied settlement of fill.
- Rory Lane and the margins of the rectangular concrete-walled channel of Arroyo Simi (Figure 2, locality 2). In the open field south of the Arroyo and east of the Simi Country Mobile Estates Park numerous deposits of fine-grained, light-colored sand resulted from ejection of water and sand along fissures or from circular holes or vents (Photo 17) as liquefaction occurred locally. The most pronounced features were long cracks next to and crossing Rory Lane (Photo 18) where as much as 10 to 12 inches (25-30 cm) of vertical displacement developed.

Photo 17. Irregular fissure along which fine sand (light tone) was ejected as well as water that soaked the surrounding ground (dark tone) in an open field just south of the intersection of White Oak Creek channel and Arroyo Simi channel, directly east of Simi Country Mobile Estates Park, Simi Valley. Features are primary evidence of liquefaction. View to southeast. Photo by P. J. Irvine, 1/25/94.

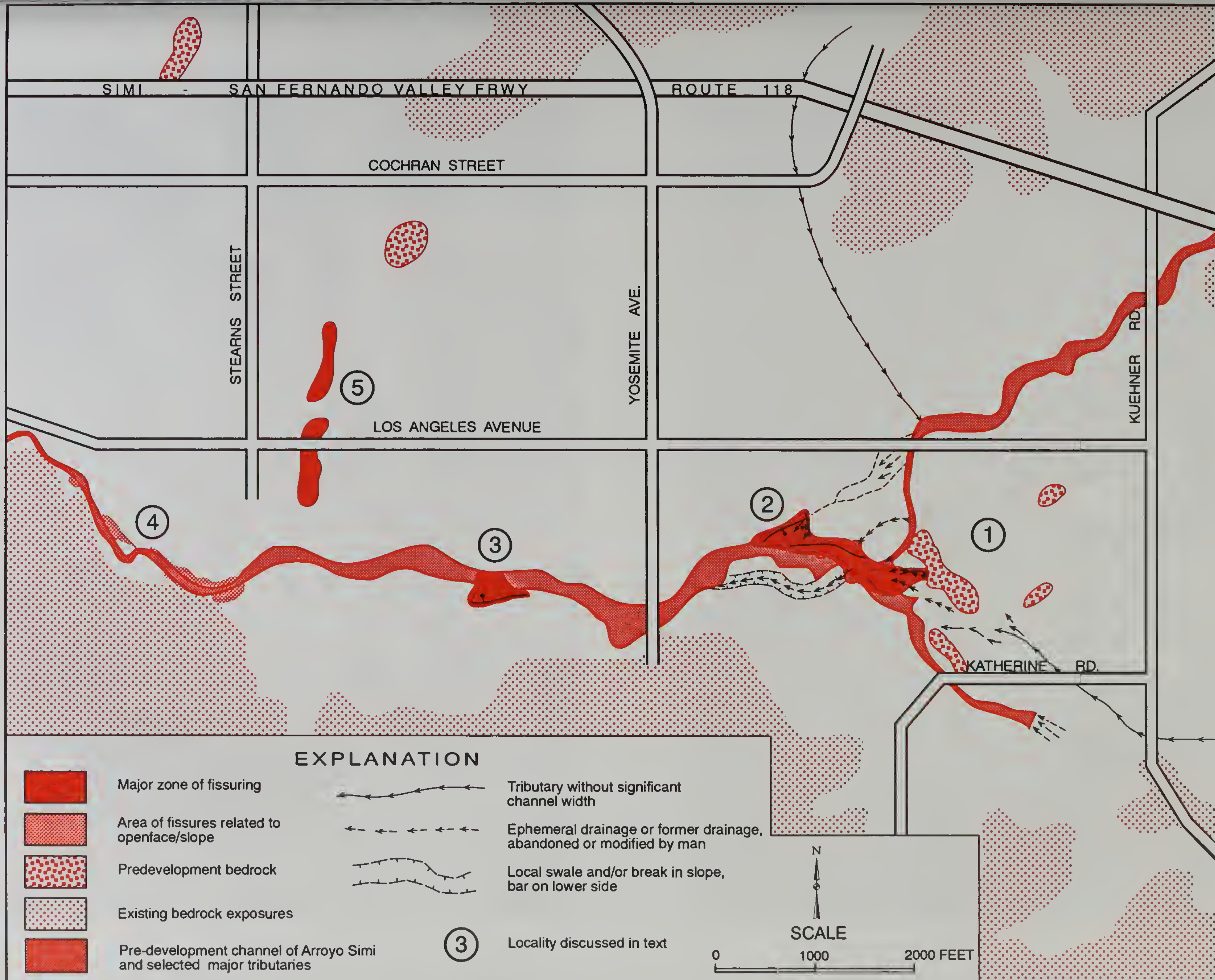


Figure 2. Map of southeastern Simi Valley showing localities of selected geologic surface effects from the Northridge earthquake discussed in the text and pre-development position of Arroyo Simi and its tributaries

Photo 18. Prominent north-trending fissure, which crosses graded fill pad east of Rory Lane in Simi Valley, exhibited as much as 12 inches (30 cm) of vertical displacement, down on the west (toward Arroyo Simi). This feature appears to be related to differential settlement, combined with possible lateral spreading, of fill above old channel deposits. Photo by P.J. Irvine, 1/25/94.

Photo 19. View eastward toward prominent, deep cracks and fissures due to lateral spreading and slumping of fractured, brittle fill materials along south side of Arroyo Simi, south of the Metrolink Station in Simi Valley. Photo by J. Fields, City of Simi Valley, taken 2/11/94.

- Stow Street to Stearns Street where the Arroyo Simi flows in a trapezoidal channel (Figure 2, locality 3). The most common effects along this interval were irregular, discontinuous extensional cracks and minor changes in the level of local stretches of the fill material bordering the sloping channel lining. However, severe structural damage to houses south of and within 300 feet (100 m) of the Arroyo was associated with local ground failure and cracking in an area where the water table is within 6 to 10 feet (2 to 3 m) of the surface.
- Unlined Arroyo Simi channel west of Stearns Street (Figure 2, locality 4). Spectacular ground-failure features, primarily long, deep fissures, downdropped blocks, and tilted blocks of the surface materials developed along the banks of the Arroyo (Photo 19). The dramatic disruption of the channel banks was due to a combination of liquefaction-induced lateral spreading and failure by lurching of the materials near the open banks.
- East of Stearns between Los Angeles Avenue and Cochran Street (Figure 2, locality 5). Between 500 and 600 feet (150-180 m) east of Stearns Street a north-south-trending zone of ground fissures, concentrated structural damage, and abundant pavement cracking developed. Although more speculative, it is possible that this zone of effects developed in response to strong shaking of the thin cover above a shallow bedrock ridge that aligns with the features.

The primary conclusions from the study of the geologic, topographic and hydrologic conditions in the area where the surface effects from the Northridge earthquake were most intensively developed include:

- Major fissures, cracks and downwarping due to differential settlement, and other ground-failure features developed essentially exclusively in areas where artificial fill had been placed upon natural stream deposits that coincide with the pre-development position of Arroyo Simi and its tributaries.
- The major cracks with significant vertical displacement closely correspond to the location of the now-buried natural banks of the pre-development Arroyo Simi (Rory Lane and Sabina Circle cracks) or with the position of tributary channels (Christine Avenue).
- The spectacular fissured ground bordering Arroyo Simi west of the railroad bridge, resulting from lateral spreading toward unsupported free faces, probably developed in response to strong vibratory motion affecting artificial fill emplaced during the channelization of the Arroyo.
- In southeastern Simi Valley, direct evidence of liquefaction (sand boils, sand craters, or fissures where water was ejected during the earthquake) was only observed or reported at locations that are situated in fill material overlying the pre-development course of Arroyo Simi where the water table is very shallow (10 feet or less).
- The extensive cracking and accompanying widespread damage in the area east of Stearns Street between Los Angeles and Cochran was not due to liquefaction. This area overlies a shallowly buried bedrock ridge and the eastern edge of a groundwater cascade that separates the eastern basin from the main groundwater basin to the west in Simi Valley. The consistent down-on-the-west displacement observed on the most prominent ground cracks implies that the concentration of effects in this area may be a result of differences in the settlement of the thick alluvial fill on the west in contrast to less settlement in the thinner eastern fill.

RIDGETOP SHATTERING

On the tops of narrow, sharp ridges, predominantly within steeply dipping sedimentary rocks, a combination of natural conditions exists, within the region affected by the Northridge earthquake, that leads to ridgetop soils acting as a "seismoscope" that dramatically records violent shaking and manifests it in a spectacular way. This phenomenon has been referred to as "shattered ridge tops" or the "tossed earth" effect (Barrows, 1975, p.108). Shattered ridge tops resemble "plowed ground," where a typically thin, brittle soil cap is thoroughly disrupted into a jumble of chunks of soil and blocks of sod, some of which are turned upside down (Photo 20).

Ridgetop shattering triggered by the Northridge earthquake was observed in the San Gabriel Mountains, the Santa Susana Mountains, the Santa Clarita area, above Tapo Canyon, and in the Santa Monica Mountains (see localities on Figure 1). Shattered ridges developed mostly north of the epicenter, especially in rugged terrain beyond the periphery of the projected area enclosing the primary fault rupture surface (at depth). Ridge tops were shattered as much as 22 miles (35 km) north of the epicenter, near Loma Verde in the Val Verde quadrangle (Figure 1, locality 12), which corresponds with the observed limit of large, coherent landslides as discussed above. Shattered fill was observed in places along the top of the Santa Monica Mountains up to 10 miles (16 km) southeast of the epicenter (Photo 21).

Photo 20. Southwest-trending shattered ridgetop in Saugus Formation sandstone 0.5 mile (0.8 km) east of the junction of Interstate 5 and State Highway 126 (Castaic Junction). Photo by S.S. Tan, 1/22/94.

All of the observed shattered ridgetops lie within areas of Modified Mercalli Intensity VII or VIII as depicted on isoseismal maps prepared by the Office of Emergency Services. The area within which these effects were produced encompasses nearly 315 square miles (817 km²). This contrasts significantly with the 34-square mile (88 km²) area within which shattered ridges were mapped after the 1971 San Fernando earthquake (Barrows and others, 1975a, Plate 1). Shattered ridgetops from the San Fernando earthquake were densely clustered in the foothill region immediately north of and within a mile or two of the actual surface fault breaks. Detailed geologic mapping demonstrated a correlation between specific lithologic units and localization of the effect. Most of the ridgetops that shattered were within fine- to coarse-grained sandstone beds of the Towsley-Pico formations or Saugus Formation. Northridge-earthquake triggered shattered ridges also developed in areas underlain by steeply dipping sandstone beds of the Saugus Formation or Pico Formation.

In several instances, tossed-earth effects developed in the same places during both the 1971 and the 1994 earthquakes. One such place, four miles north of the mouth of Little Tujunga Canyon (Figure 1, locality 15), is in dark, reddish, adobe-like, old terrace deposits crossed by Little Tujunga Road (Photo 22), in the vicinity of the Watt and De Mille faults (Oakeshott, 1958, Plate 1). Landslides and roadcut failures were concentrated in this same locality. Apparently, shaking energy was magnified or focused where contrasting rocks are juxtaposed along these fault planes. Two miles (3.2 km) to the west, along the top of Kagel Mountain (Photo 23), just east of Pacoima Dam where extremely strong ground motion (in excess of 2g) was recorded, shattered ridges and numerous ridgetop cracks developed in places where surface cracks formed in 1971 also in response to very intense shaking (Figure 1, locality 16).

Photo 21. Shattered fill material along north side of Mulholland Drive, east of Benedict Canyon, Sherman Oaks, Santa Monica Mountains. Photo by S.S. Tan, 1/18/94.

Photo 22. Jumble of blocks from shattered soil cap on old alluvium in roadcut along Little Tujunga Road in the vicinity of the traces of the Watt Fault and the De Mille strand of the San Gabriel Fault, 4 miles (6.4 km) north of the mouth of Little Tujunga Canyon. Photo by A.G. Barrows, 1/20/94.

Photo 23. Shattered ridgetop in thin soils on gneissic rock along the crest of Kagel Mountain about one mile (1.6 km) east of Pacoima Dam. Photo by A.G. Barrows, 1/20/94.

LIQUEFACTION AND LATERAL SPREADING

The Liquefaction Process

Liquefaction was initiated in many widely scattered localities during the relatively short interval of strong shaking and intense ground motion that accompanied the Northridge earthquake.

Liquefaction is a transitory phenomenon that causes water-saturated, cohesionless granular materials, such as fine sand, to change into a fluidlike state when they are subjected to powerful shaking. As a result, such material loses its ability to resist deformation and support a load. The ground above liquefied materials commonly deforms or fails before the material returns to a state of rest. It is this ground failure that primarily causes damage to structures, pavement, and underground pipelines. It is important to recognize, as the examples listed below demonstrate, that most of the actual *damage* connected with liquefaction during the Northridge earthquake occurred where inadequately prepared fill materials experienced failure through cracking, distortion, and settlement.

Where liquefaction occurs, typical surficial manifestations include sand boils or sand "volcanoes," linear arrays of sand craters (Photo 17), extensional cracks, distortion of the ground due to settling, and lateral displacement of small to large masses of soil or blocks of material (Photo 19). Some of these features, such as cracking and tilting of the ground surface, can result from other processes including compaction and consolidation of loose, unsaturated fill materials. The occurrence of sand boils and craters, or groups of subparallel scarplike cracks and graben near the edges of channels or other areas where the water table is shallow, is considered unequivocal evidence that liquefaction has occurred.

The geologic and groundwater conditions that favor the occurrence of liquefaction – water-saturated, loose, granular sediments at shallow depths – are typically present in the following environments: present and former river channels and floodplains, inland lakes and ponds, and coastal lagoons, marshes, and beaches. Liquefaction during the Northridge earthquake primarily occurred in three surroundings: along coastal margins, around man-made flood basins in inland valleys, and in or adjacent to current or former drainage channels.

Distribution

Selected localities where evidence of liquefaction triggered by the Northridge earthquake was noted are plotted on Figure 1. Liquefaction effects were seen 38 miles (60 km) north of the epicenter along Gorman Creek in Lower Hungry Valley (Figure 1, locality 17), 44 miles (70 km) to the west at the mouth of the Santa Clara River in the Ventura/ Oxnard area (Figure 1, locality 18), 10 miles (16km) to the east in the Hansen Flood Control Basin (Figure 1, locality 19), and 36 miles (57 km) to the south at the Port of Los Angeles in San Pedro (Figure 1, locality 20). The total area of the region within which manifestations of liquefaction were observed is approximately 1218 square miles (3154 km^2). Although the area affected by liquefaction is only about 42 percent of the area affected by rockfalls and landslides, it is much larger than the area where liquefaction occurred during the 1971 San Fernando earthquake.

Coastal Margins

Liquefaction occurred in coastal alluvial floodplain and estuarine sediments, in natural and artificial beach deposits, and in man-made fills placed upon natural beach and lagoonal sediments. The most common surface expression of the process in these environments is sand boils, craters (Photo 24), fissures, and lateral spreading cracks. Liquefaction occurred in the following coastal areas:

- mouth of the Santa Clara River in Oxnard/Ventura (Figure 1, locality 18)
- beaches north of the Santa Monica Pier
- artificial beach at Marina Del Rey
- artificial fill in Port of Los Angeles (Figure 1, locality 20)
- artificial fill at King Harbor in Redondo Beach (Figure 1, locality 21)

Most of these areas experienced little or no damage except for the places where artificial fill failed by lateral spreading and settlement at King Harbor Marina (Photos 25 and 26) and at the Port of Los Angeles.

Inland Basins

Liquefaction occurred in and around the perimeter of several man-made flood-control basins on the broad alluvial floodplain within the San Fernando Valley. Sand boils, sand fissures, and ground cracks accompanying lateral spreading caused minor to moderate damage to pond embankments, pavement, and buried pipelines. Once again, damage occurred primarily where artificial fill experienced problems. Although liquefaction affected some of the same localities that it did during the 1971 San Fernando earthquake, the results were minor compared to the liquefaction-related, nearly catastrophic, destruction of the old Lower Van Norman Dam. Inland basin areas known to have been affected by liquefaction include:

- San Fernando Power Plant Tailrace
- Upper Van Norman Lake
- Joseph Jensen Filtration Plant
- lake bed area upstream of Hansen Dam

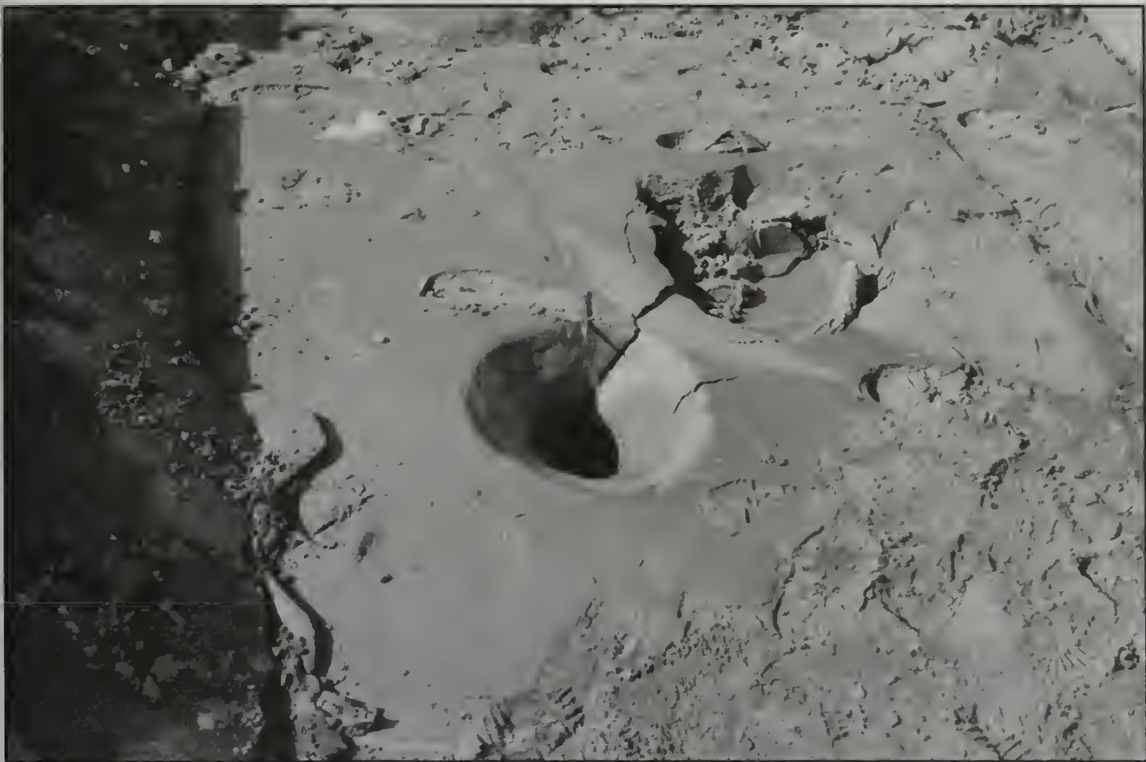


Photo 24. Sand boil or sand "volcano" resulting from liquefaction of fine-grained fill material derived from sand dunes that was emplaced over former beach and lagoonal deposits to create Mole B, King Harbor Marina, Redondo Beach. Note uniformity of material and slick, moist surface from ejected water on slopes of boil. Photo by S.S. Tan, 1/20/94.

Current and Former Drainage Channels

Liquefaction occurred in shallow alluvial and colluvial deposits in and adjacent to active stream and river channels, in buried channels and adjacent areas. Most areas experienced little or no damage from liquefaction except in southeastern Simi Valley (discussed above) and a failed tailings pond and dam in Tapo Canyon north of Simi Valley (Figure 1, locality 22). Liquefaction occurred in the following drainage channels:

- Gorman Creek near Lower Hungry Valley (Figure 1, locality 17)
- Santa Clara River between Fillmore and Newhall
- Santa Clara River near Saugus
- Santa Clara River between Mint and Sand Canyons
- Los Angeles River west of Reseda Boulevard
- Potrero Canyon
- Gillibrand Canyon north of Simi Valley
- Tapo Canyon north of Simi Valley (Figure 1, locality 22)
- Arroyo Simi in southeast Simi Valley
- Marsh area north of Arroyo Simi, NW Simi Valley
- Bull Canyon in the San Fernando Valley

Photo 25. Shattered pavement, chaotically disrupted by liquefaction-related lateral spreading of fine-grained sandy fill materials along Mole B, King Harbor Marina, Redondo Beach. Photo by S.S. Tan, 1/20/94.

Photo 26. Failed south-facing retaining wall along Mole B, King Harbor Marina, Redondo Beach. Note cone of fine sand at base of crack, left of center. Wall was deflected about 17 feet (5 m) from original position as a result of lateral spreading. Photo by S.S. Tan, 1/20/94.

It is worth noting that all of the areas listed above, where evidence of liquefaction resulting from the Northridge earthquake was observed, had been previously designated as having high liquefaction potential in the Safety Elements of the General Plans of the local jurisdictions affected. Observations of the effects of the Northridge earthquake make it clear that in order to mitigate liquefaction-caused damage in the future more attention must be placed upon proper engineering and preparation of artificial fill.

SETTLEMENT AND CRACKING OF FILLS

Distortion due to differential settlement and, locally, failure by cracking of man-made fill caused minor to severe damage to structures, building pads, and, especially, highways throughout the region affected by strong shaking during the earthquake. Although Division geologists did not conduct investigations of fill performance, except in Simi Valley and Sherman Oaks as summarized above, they did record observations of fill movement during the post-earthquake field search for geologic surface effects such as slope failures, liquefaction phenomena, and ground cracks.

Fill damage was observed in older road fills, in building pads regardless of age, in fills within stream channels and gullies, and in the loose, sandy materials used in the construction of marina facilities. Settlement of tapering, triangular fills, called wedges, and cracked pavement was common along many of the mountain roads such as the Santa Susana Pass Road where it enters Simi Valley and Mulholland Drive along the top of the Santa Monica Mountains. Damage to fills constructed during grading in hillside areas was widespread but appeared to be concentrated in two places – along the northern slope of the Santa Monica Mountains (see Sherman Oaks discussion above) and along hillsides and ridges in the Santa Clarita region. In low-lying areas, such as southeastern Simi Valley, numerous dwellings were destroyed because of ground failure in old fill material emplaced upon old channel deposits of Arroyo Simi (see discussion above). The most spectacular manifestations of liquefaction-induced failure of fine, sandy fill occurred at King Harbor in Redondo Beach, where fill failed behind the harbor wall causing damage to a bulkhead and pipeline breakage (see liquefaction discussion and Photos 25 and 26).

Seismically induced damage of man-made fills during the Northridge earthquake resulted from one or several of many different factors. Fills placed near the top or at the nose of a narrow ridge or above a shallowly buried bedrock ridge were subject in many places to amplification of shaking and stronger ground motion. Along the upper portion of the "daylight" line of wedge fills, where emplaced material abuts a surface cut in bedrock or other native materials, settlement and cracking of building pads was especially common. This was due to differences in the response of the contrasting materials to strong shaking and, possibly, to downslope movement of the hillside fill. In other places, fills were damaged where underlying weak bedrock or existing landslide deposits moved downslope, even slightly. Liquefaction and related lateral spreading of fill or materials beneath the fill resulted, locally, in chaotic disruption of the surface (Photo 25 and 26). Compaction or consolidation of inadequately engineered fill in response to strong shaking was also widespread. Naturally, site-specific investigations are necessary to determine which of these factors played a role in local fill failure.

A compilation of case histories of seismically induced fill movement resulting from the Northridge earthquake has been prepared by geotechnical consultants Alan Kropp and Associates, in cooperation with Raymond Seed of the College of Engineering, University of California at Berkeley (Stewart and others, 1994). The published report contains a regional locality map of damaged fills and a discussion of the performance of hillside structural fills. Additional studies by these investigators, consisting of collection and analysis of site-specific data, are currently underway as part of a National Science Foundation Grant entitled "Earthquake-Induced Movements of Wedge Fills."

CONCLUSIONS

Observations of the surface geologic effects and the damage associated with them point to a number of conclusions about the area affected by the Northridge earthquake. Although the Northridge earthquake was not the highest magnitude event to affect California in historic time, it was certainly the most costly and the most violent to strike the greater Los Angeles region, as reflected in its extremely high recorded ground motions.

- Extent of effects. Compared to the similar-size 1971 San Fernando earthquake, which struck the same region, the Northridge earthquake triggered rockfalls and landslides over an area that is more than twice as big. Ridgetop shattering, a manifestation of highly amplified shaking, occurred over a region nearly ten times greater in 1994 than it did in 1971. Liquefaction effects developed over an area that is also much larger than that affected in 1971.
- Landslides. The great majority of the more than 11,000 slope failures triggered by the earthquake were very shallow and caused little damage except for temporarily interrupting transportation routes. More damage to the works of man resulted from the movement and reactivation of bedrock landslides than the numerous rockfalls and debris slides. Essentially all of the seismically triggered landslides occurred in areas of pre-existing landslides or where slopes had already been assessed to be highly susceptible to slope failure.
- Liquefaction. Most damage to man-made structures from liquefaction-related ground failure occurred in areas underlain by poorly engineered or inadequately prepared artificial fill materials.
- Damage related to cracking or settlement of artificial fill was widespread and, in many cases, coincided with the location of incipient cracks or minor surface deformation that existed prior to the earthquake. Fill failure that led to damage was especially common along the upper portion of the "daylight line" of hillside wedge fills or where thin, small fill bodies settled. It appears that the earthquake essentially "sped up" the process of deformation associated with slowly deteriorating fill that might occur over a much longer time period.
- Even though the geologic surface effects are abundant, widely distributed, and, locally, spectacular, only a very small amount (less than 5 percent) of the total earthquake damage to man-made structures can be directly related to the observed effects such as ground failure.

ACKNOWLEDGMENTS

In preparing this summary, we benefitted from the observations shared by Division of Mines and Geology colleagues from their rapid reconnaissance of the area affected by the Northridge earthquake. We are especially grateful to Division geologists Jerome Treiman, Dinah Shumway, Tim McCrink, and Mark DeLisle. We thank Randy Jibson and Ed Harp of the U.S. Geological Survey for sharing information about the distribution of landslides in the region.

REFERENCES

Barrows, A.G., 1975, Surface effects and related geology of the San Fernando earthquake in the foothill region between Little Tujunga and Wilson canyons, *in* Oakeshott, G.B., ed., San Fernando, California, earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, p. 97-117.

Barrows, A.G., 1986, Landslide hazards in the east half of the Val Verde quadrangle, Los Angeles County, California: Division of Mines and Geology Open-File Report 86-9, map scale 1:24,000.

Barrows, A.G., 1993, Rockfalls and surface effects other than faulting, Landers and Big Bear earthquakes: California Geology, v. 46, no.1, p. 17-22.

Barrows, A.G., Kahle, J.E., Weber, F.H., Jr., and Saul, R.B., 1975a, Map of surface breaks resulting from the San Fernando earthquake of February 9, 1971, *in* Oakeshott, G.B., ed., San Fernando, California, earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, Plate 1, map scale 1:24,000.

Barrows, A.G., Kahle, J.E., Saul, R.B., and Weber, F.H., Jr., 1975b, Geologic map of the San Fernando earthquake area, *in* Oakehott, G.B., ed., San Fernando, California, earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, Plate 2, map scale 1:18,000.

Barrows, A.G., Tan, S.S., and Irvine, P.J., 1994, Investigation of surface geologic effects and related land movement in the City of Simi Valley resulting from the Northridge earthquake of January 17, 1994: Division of Mines and Geology Open-File Report 94-09, 42 p., map scale 1:6,000.

Campbell, R.H. 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Dibblee, T.W., Jr., 1991, Geologic map of the Beverly Hills and Van Nuys (south 1/2) quadrangles, Los Angeles County, California: Dibblee Geological Foundation Map DF-31, map scale 1:24,000.

Dibblee, T.W., Jr., 1993, Geologic map of the Val Verde quadrangle, Los Angeles and Ventura counties, California: Dibblee Geological Foundation Map DF-50, map scale 1:24,000.

Harp, E.L., and Jibson, R.W., 1995, Landslides triggered by the January 17, 1994 Northridge, California earthquake: U.S. Geological Survey Open-File Report 95-213, Plate 1 scale 1:100,000; Plate 2 scale 1:50,000.

Irvine, P.J., 1990, Landslide hazards in the Simi Valley area, Los Angeles and Ventura counties, California: Division of Mines and Geology Open-File Report 90-17, map scale 1:24,000.

Keefer, D.K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

Morton, D.M., 1975, Seismically triggered landslides in the area above the San Fernando Valley, *in* Oakeshott, G.B., editor, San Fernando, California, earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, p. 145-154.

Oakeshott, G.B., 1958, Geology and mineral deposits of San Fernando quadrangle, Los Angeles County, California: California Division of Mines Bulletin 172, 147 p.

Saul, R.B., 1979, Geology of the southeast 1/4 Oat Mountain quadrangle, Los Angeles County, California: California Division of Mines and Geology Map Sheet 30, map scale 1:12,000.

Shakal, A., Huang, M., Darragh, R., Cao, T., Sherburne, R., Malhotra, P., Cramer, C., Sydnor, R., Graizer, V., Maldonado, G., Petersen, C., and Wampole, J., 1994, CSMIP strong-motion records from the Northridge earthquake of 17 January 1994: Division of Mines and Geology Office of Strong Motion Studies Report OSMS 94-07, 308 p.

Stewart, J.P., Bray, J.D., Seed, R.B., and Sitar, Nicholas, editors, 1994, Preliminary report on the principal geotechnical aspects of the January 17, 1994 Northridge earthquake: University of California at Berkeley, College of Engineering Report No. UCB/EERC - 94/08, 245 p.

Tan, S.S., 1995, Landslide hazards and effects of the Northridge earthquake of January 17, 1994 in the southern part of the Van Nuys quadrangle, Los Angeles County, California: Division of Mines and Geology Open-File Report 95-02, map scale 1:12,000.

Treiman, J.A., 1986, Landslide hazards in the west half of the Newhall quadrangle, Los Angeles County, California: Division of Mines and Geology Open-File Report 86-6, map scale 1:24,000.

Treiman, J.A., 1987, Landslide hazards in the north half of the Oat Mountain quadrangle, Los Angeles County, California: Division of Mines and Geology Open-File Report 87-08, map scale 1:24,000.

Weber, F.H., Jr., 1980, Landsliding and flooding in southern California during the winter of 1979-80: California Division of Mines and Geology Open-File Report 80-3, 69 p.

Weber, F.H., Jr., Treiman, J.A., Tan, S.S., and Miller, R.V., 1978, Landslides in the Los Angeles region, California – Effects of February-March 1978 rains: California Division of Mines and Geology Open-File Report 79-4, 265 p.

Winterer, E.L., and Durham, D.I., 1962, Geology of the southeastern Ventura Basin, Los Angeles County, California: U.S. Geological Survey Professional Paper 334-H, 364 p., map scale 1:24,000.

Hart, E.W., Treiman, J.A., and Bryant, W.A., 1995, The search for fault rupture after the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 89-101.

THE SEARCH FOR FAULT RUPTURE AFTER THE NORTHRIDGE EARTHQUAKE

by

Earl W. Hart[1], Jerome A. Treiman[2], and William A. Bryant[3]

INTRODUCTION

The 17 January 1994 Northridge earthquake was a surprise to geologists in two ways: (1) it occurred on a previously unknown thrust fault and (2) it produced virtually no surface faulting. Perhaps we should not be surprised at this because other recent earthquakes at Coalinga (1983; M 6.3), Whittier Narrows (1987; M 5.9), Loma Prieta (1989; M 7.1), and Petrolia (1992; M 7.0) all occurred on blind faults that produced no primary surface faulting. In contrast, the nearby 1971 San Fernando earthquake, which was the same magnitude as the Northridge earthquake (M 6.7), produced abundant surface faulting and was responsible for the enactment of the Alquist-Priolo Earthquake Fault Zoning Act. This act was initially called the Alquist-Priolo Geologic Hazards Zones Act in 1972 and was designated as the Alquist-Priolo Special Studies Zones Act from 1975 until January 1, 1994. This act regulates development within Earthquake Fault Zones in order to locate structures for human occupancy away from the traces of active faults. The primary purpose of the act is to mitigate the hazard of surface faulting.

Based on seismic data, the Northridge earthquake originated on a 40°-south-dipping thrust fault at a depth of about 19 km. The hanging wall (upper plate) was thrust up and to the north toward the Santa Susana Mountains, with initial rupture stopping 6-8 km below the ground surface. According to Wald and Heaton (1994), the fault has a strike of N 58°W. The calculated average slip at depth was 1.2 m over the rupture area with a maximum of nearly 4 m. The inclined rupture area was 14 km along strike and 20 km in an up-dip direction. Aftershock distribution was very diffuse in the upper 6 to 8 km and distributed under the Santa Susana Mountains and adjacent San Fernando Valley. The Santa Susana Mountains contain numerous thrust faults and folds indicative of a broad zone of late Cenozoic compression (Yeats and others, 1994). Global Positioning Satellite data (USGS AND SCEC, 1994) indicate that the Santa Susana Mountains were uplifted as much as 70 cm and displaced horizontally as much as 21 cm, which is generally consistent with the seismic data (i.e., northward thrusting) and the neotectonics.

THE SEARCH FOR FAULT RUPTURE

Geologists of the Department of Conservation, Division of Mines and Geology (DMG), along with numerous other geologists from the U.S. Geological Survey, universities, and industry, responded quickly to check for surface faulting and other ground failures. DMG's Fault Evaluation and Zoning Project has the official responsibility of mapping fault rupture after earthquakes in California. The main purpose of this response is to (1) accurately map surface faulting before evidence of it is destroyed, and (2) evaluate the effectiveness of our previous mapping and zoning under the Alquist-Priolo Act. A secondary purpose is to observe the effects of surface faulting on structures.

Initial response focused on a field check of the known late Quaternary faults and those faults that ruptured in

[1]California Department of Conservation, Division of Mines and Geology, San Francisco, California
[2]California Department of Conservation, Division of Mines and Geology, Los Angeles, California
[3]California Department of Conservation, Division of Mines and Geology, Sacramento, California

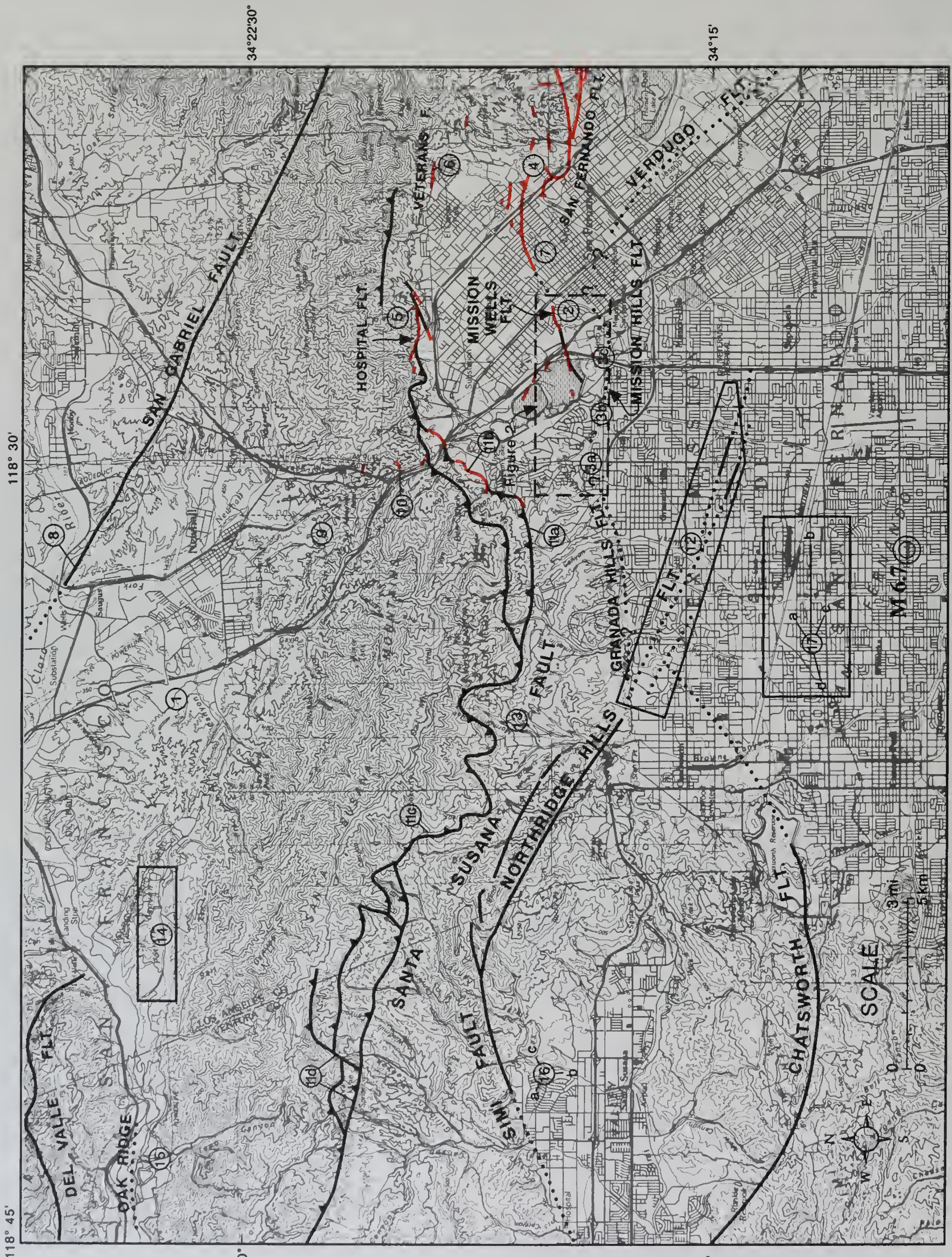


Figure 1. Location of surface fault rupture (localities 1-2) and other ground rupture localities (3-17) associated with the Northridge earthquake of January 17, 1994. Principal late Quaternary faults, the 1994 earthquake epicenter, and the 1971 fault ruptures (heavy lines) are shown.

the 1971 San Fernando earthquake (Figure 1). Another important part of the search for ground rupture involved the follow-up to reports from many sources of possible fault rupture. In addition to data from private and government geologists, reports came into the State-operated Clearinghouse from homeowners and other untrained observers. All reports received were considered and most localities were visited in the field. The vast majority of the reported ground effects involved cracks attributable to shaking, including ridgetop shattering, landsliding, lateral spreading, settlement, and liquefaction. Early coordination with the U.S. Geological Survey left detailed study of two areas (Granada Hills and Potrero Canyon) to their scientists (see articles by Hecker and others and Rymer and others, this volume) while DMG geologists continued to follow up on reported cracks and focus on other areas. After checking crack localities for two weeks, it became apparent that there was very little surface fault rupture. Our field observations and data collection efforts were subsequently reduced. Some of these rupture localities are described below.

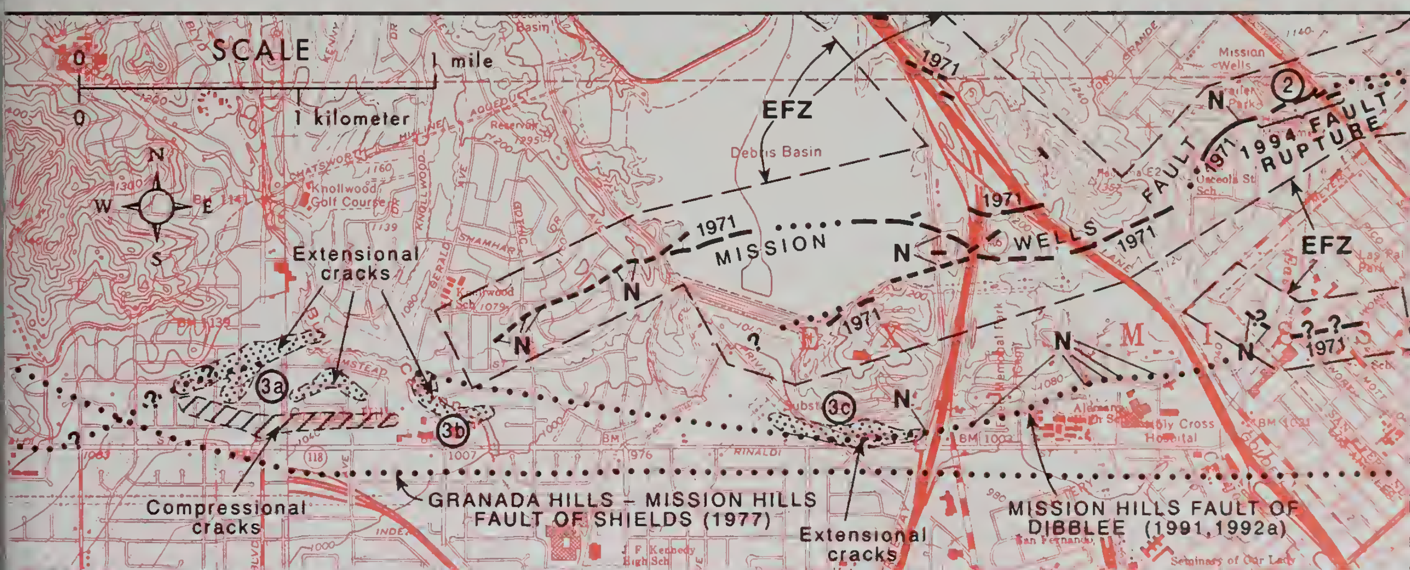
Of mixed utility were the available post-earthquake aerial photos of the affected region. Photos taken for the USGS in the area of reported ruptures (Potrero Canyon and Granada Hills) were of adequate scale (1:1,000, 1:2,000 and 1:6,000) but of limited area. NASA and the U.S. Air Force photos, also flown shortly after the earthquake, were too small-scale (1:15,000 and smaller-scale) to be of much use in identifying fault rupture and other ground cracks, although they were useful for plotting landslide data.

SUMMARY OF OBSERVATIONS

Very little of the ground rupture that formed during the Northridge earthquake was caused by fault rupture, and that which did occur was either on secondary structures or was triggered slip (i.e., faulting triggered by shaking). In fact, only two localities had clear evidence of fault rupture (Localities 1 and 2, Figure 1). Other faults also had minor associated ground rupture, but nearly all of this appears to be due to landsliding, lateral spreading and other shaking effects (Localities 3 to 13, Figure 1). Several additional rupture localities, initially thought by others to be fault rupture, ultimately proved to be caused by shaking (Localities 14-17, Figure 1). These localities are described below and identified on Figures 1 and 2, and summarized on Table 1.

Fault Rupture Localities

Flexural-slip faulting at Stevenson Ranch. The most significant fault ruptures occurred as flexural slip on the northeast flank of the Pico Anticline at the Stevenson Ranch subdivision west of Newhall (Locality 1, Figure 1). Five bedding-plane ruptures, with a maximum of 19 cm of vertical offset, were identified here in a zone 130 m wide and 500 m long. The faults offset roads and building pads of the new subdivision and apparently extended in a N 35°W direction across a closed depression and an undeveloped hillside. Deep trench excavations revealed evidence of extensive bedding-plane shears, indicating multiple previous events. Bending-moment thrust faults at a sharp flexure in the Pleistocene strata, which also



igure 2. Map of principal ground-crack zones caused by lateral spreading and settlement near Granada Hills during the 1994 Northridge earthquake ocalities 3a,3b,3c). Stippled areas represent extensional crack zones; diagonal lined areas are zones of compressional cracks. Also shown are arthquake Fault Zones (EFZ) that encompass 1971 fault ruptures and related fault traces (from CDMG, 1979). Segment of Mission Wells Fault, where p to 1.2 cm of left-lateral surface faulting was triggered in 1994, is identified as locality 2. N indicates no fault rupture was found where other faults ere checked in 1994. Concealed traces of Mission Hills Fault of Dibblee (1991, 1992a) and Shields (1977) shown by dotted lines.

Table 1. Summary of ground rupture localities evaluated after the Northridge earthquake and inferred rupture mechanism. See Figures 1 and 2 for locations and text for discussion.

Fault Rupture

1. Bedding-plane and possible bending-moment fault rupture at Stevenson Ranch Subdivision; flexural slip on 5 bedding planes on NE flank of Pico anticline; maximum of 19 cm of vertical offset; length of rupture zone about 500 m. Fault previously unmapped.
2. Triggered slip on east end of Mission Wells Fault; maximum of 1.2 cm left-lateral slip, 400 m of rupture length.

Other Ground Rupture Near Known Faults

3. Mission Hills Fault
   a. Broad zone of rupture 1 km long by 0.5 km wide in Granada Hills; partly defined lateral-spread feature in Holocene alluvium with extensional and left-lateral cracks on the north and northwest and compressional ruptures on south; estimated maximum displacement to south or southeast roughly 0.5 m.
   b. Slumping and settlement cracks in Bull Canyon.
   c. Incipient lateral-spread cracks in soil and alluvium.
4. Tujunga segment of San Fernando Fault — minor reopening of 1971 cracks, possibly triggered slip; cracking may be partly landslide related.
5. Hospital Fault — minor cracks in paving probably due to shaking; reopened 1971 cracks to east, probably related to landsliding.
6. Veterans Fault — cracks just south of 1971 cracks reported to be due to shaking.
7. Sylmar segment of San Fernando Fault — buckled sidewalk across 1971 warp and fault ruptures.
8. San Gabriel Fault — local cracks with possible minor right-slip in fill; cracks probably due to shaking.
9. Beacon and Weldon Faults — only minor shaking cracks in RR cut.
10. Unnamed 1971 fault reactivated with 2.5 cm of vertical slip; considered by Caltrans to be shaking/landslide related.
11. Santa Susana Fault — minor shaking cracks at one road crossing; no cracks at 3 other locations; no evidence of fault rupture.
12. Northridge Hills (concealed) Fault — no evidence of surface faulting, although hills may have been upwarped 5-10 cm (preliminary leveling data).
13. Brugher (Browns Canyon) Fault — no evidence of faulting.

Ground Cracks Not Associated With Known Faults

14. Potrero Canyon ruptures extend for length of 3 km; due to settlement and lateral spreading of valley alluvium; local association of moletrack features due to uncoupling of soil/root mat; other landslide and ridgetop spreading features nearby attest to intense shaking.
15. Large cracks at mouth of Tapo Canyon — settlement and lateral spreading of terrace and alluvial fan deposits in heavily watered orchard.
16. Simi Valley area — three areas of relatively persistent, mostly extensional cracks of various orientations; partly in older alluvium; appear to be shaking related (settlement and minor downslope movement).
17. Northridge epicentral area — widespread cracks in ground and paving; largest ruptures with up to 18 cm of right-lateral slip may be right margin of lateral-spread feature in Holocene alluvium.

may have been reactivated, are closely associated with the flexural slip ruptures. It is suspected that similar deformation may have occurred elsewhere on the flanks of folds, but would be difficult to detect on the steep slopes of the Santa Susana Mountains which also produced innumerable small landslides. These flexural slip ruptures and related deformation are discussed in greater detail by J.A. Treiman (this volume).

Mission Wells Fault. The only other definite surface faulting occurred along a 400 m segment of the Mission Wells Fault, which previously ruptured in 1971 (Locality 2, Figure 2). Displacement in 1994 was a maximum of about 1.2 cm left-lateral across a 15 m-wide zone of partly right-stepping cracks. It is believed that the recent fault rupture was a shallow strain-release triggered by shaking. The 1994 rupture compares with a maximum in 1971 of about 4 cm left-lateral slip along the same segment of the fault and 15 cm vertical and 20 cm left-lateral slip immediately to the west (Weber, 1975). No evidence of 1994 rupture was observed to the west along this fault.

Photo 1. Looking north along Balboa Boulevard which was offset by a zone of extensional and left-lateral fractures that also ruptured natural gas and water transmission lines. Fractures were determined to be caused by lateral spreading (Locality 3a, Figure 2).

Other Ground Cracks Observed Near Known Faults

Ground cracks were observed on or very close to other mapped late Quaternary faults, but few if any of these ruptures are thought to be fault-related. However, minor triggered slip possibly may have occurred on other faults at Localities 4, 8, and 10 on Figure 1.

Mission Hills Fault. A broad zone of ground and pavement ruptures developed discontinuously along the concealed trace of the Mission Hills Fault of Dibblee (1991, 1992a) for a distance of 3.5 km (Figure 2). Shields (1977), who locates this fault farther south, considers the fault to be a steeply north-dipping reverse fault with a total of 1200-1800 m of reverse displacement extending upward into Pleistocene alluvium in the subsurface. Because some of the ground ruptures appear to be systematic and to form locally continuous zones, the proximity of the ruptures to the concealed Mission Hills Fault suggested a possible tectonic relationship. The western set of the fractures (Locality 3a, Figure 2) was best developed and most persistent. The fractures to the east (Localities 3b and 3c, Figure 2), although generally aligned with the concealed Mission Hills Fault, were discontinuous and appear to be local shaking failures.

The principal ruptures were largely confined to a roughly elliptical zone nearly 1 km long by 0.5 km wide (Locality 3a, Figure 2). In the vicinity of Balboa Boulevard, the zone is defined by an extensional and left-lateral zone of cracks on the north and a compressional zone of ruptures on the south.

The extensional zone was best defined where it crossed Balboa Boulevard in an east-northeast direction, rupturing soil, paving, building foundations, and major gas and water pipelines. Leaking gas and ensuing fires burned five adjacent homes. According to O'Rourke and Palmer (1994), the 22-inch gas line pulled apart about 25 cm here, but it compressed an equal amount across the zone of compression 350 m to the south. Interestingly, three other newer pipelines (two gas, one fuel) along Balboa did not fail. The paving on Balboa developed a narrow sag or graben along the extensional ruptures and the sidewalks and curbs on both sides of the street showed systematic left-lateral offset (Photo 1). The entire zone of extension was at least 100 m wide in some places, however. A 4.5 m-deep trench near the east end of the zone showed the main rupture zone to be a few meters wide and to offset late (?) Holocene alluvium perhaps 10 cm (down to the south). The ruptures did not increase with depth and showed no evidence of previous

Photo 2. Northeast-trending extensional ground cracks in lateral spread feature (Locality 3a, Figure 2) east of Balboa Boulevard. Concrete block wall is pulled apart about 15 cm. Nearby houses and swimming pool also were damaged by ground ruptures.

rupture. Similar features were reported in two trenches just west of Balboa (Hecker and others, this volume). A shorter, more irregular zone of extensional and left-lateral ruptures developed to the southeast of the main extensional zone (Photo 2).

The southern margin of the presumed lateral-spread feature is marked by a broad zone of compressional features, including buckled and overthrust sidewalks, paving, and curbs, as well as three telescoped pipelines (Photo 3). A striking example of the general north-south compression was observed at 16915 Flanders Street where the concrete driveway approach apparently was pushed southward at least 25 cm under the asphalt street paving (Photo 4). The continuous concrete paving to the house and attached garage to the north showed no comparably large extensional cracks. Large extension cracks also were absent from the house foundation and the ground immediately behind it. On the opposite (south) side of Flanders a few centimeters of compression were observed in the asphalt driveway adjacent to the sidewalk, again without extensional fractures between the house and street. Both of these houses also were thrown 5-8 cm off their foundations to the south and rotated in a clockwise manner. An apparent shortening of more than 25 cm occurred between these two house without any apparent intervening fault. It appears that the house on the north side of the street and its foundation and adjacent paving uncoupled from the ground and moved southward.

Other evidence that lateral spreading was operative at Locality 3a, Figure 2, is supported by preliminary survey data by the City of Los Angeles which shows that the north-south streets lengthened a maximum of about 0.5 m across the extensional zones and shortened nearly that much across the compressional zone. This also was consistent with surveys and observations of the U.S. Geological Survey (Hecker and others, this volume). When viewed in conjunction with the geometry of the extensional and compressional rupture zones (which die out laterally as they approach each other) and the discontinuous and distributive nature of cracking, evidence for lateral spreading seems compelling.

Other extensional and compressional cracks were noted in Bull Canyon (Locality 3b, Figure 2) immediately to the east of the rupture zone described above. Reconnaissance mapping shows these fractures to closely follow the drainage margins, including the bend in the canyon, and to have no connection with the cracks to the west. The cracks appear to be caused by shaking-induced slumping of the stream bank and possibly local settlement of the stream deposits. They do not appear to be related to the lateral spread features of Locality 3a, Figure 2.

About 1.5 km farther to the east is a 700 m-long zone of discontinuous, extensional cracks at the base of the hills just west of Highway I-405 that coincide with Dibblee's (1991) concealed trace of the Mission Hills Fault (Locality 3c). At the east end of the observed zone, a small (less than 5 mm) component of right-slip was measured on individual cracks at Blucher Avenue and Midwood Drive. West of Midwood Drive the crack zone was 60-100 m wide and could be followed for another 400 m. Extensional displacement increased to the west

Photo 3. Zone of compression at the toe (south margin) of a lateral spread feature caused this pipeline to telescope at least 25 cm and the adjacent street and sidewalks of Balboa Boulevard to buckle. Locality 3a, Figure 2, about 350 m south of Photo 1.

where the zone curved to the west-northwest toward an electrical power substation. Although minor faulting cannot be ruled out, distributed cracks at the west end of the zone paralleled the contours and clearly were due to lateral spreading. Other cracks distributed on the hillslope northwest of Midwood Drive also appeared to be related to downslope movement caused by shaking. Reconnaissance mapping between Localities 3b and 3c revealed only minor and very discontinuous cracks, none of which appeared to be fault-related. See Hecker and others (this volume) for additional observations.

Tujunga Segment of San Fernando Fault. Minor reopening of 1971 cracks occurred at the west end of the fault (Locality 4, Figure 1), but no systematic or measurable displacements were reported by DMG (Allan Barrows, 1994, personal communication). A geologic consultant (Joe Cota, Geosoils, 1994, personal communication) also reported reactivation of 1971 cracks but thought they may be related to landslide cracks developed on a hill to the east.

Hospital Fault. Very minor, east-trending extension cracks were observed in a concrete culvert at the end of Cobalt Avenue (where 4-6 cm left-lateral faulting was reported in 1971) (Locality 5, Figure 1). The cracks could not be traced into the soil and were probably shaking effects; other minor cracks were observed in a concrete street to the south. To the east, near Olive View Hospital Bldg. #401, which was abandoned after the 1971 earthquake, right-stepping, northeast-trending cracks in asphalt were slightly reopened (less than 1 cm?) in 1994. This is the margin of a landslide mapped in 1971 (Barrows and others, 1975), although the crack zone has a right-stepping relationship to and the same trend as the 1971 fault ruptures previously mapped to the west.

Veterans Fault. No cracks were observed along this 1971 fault trace. However, a geologic consultant (Joe Cota, 1994, personal communication) observed an east-trending crack with 5 cm of extension in Tucker Street just south of the 1971 fault rupture (Locality 6, Figure 1). We did not check this locality.

Sylmar Segment of San Fernando Fault. A buckled sidewalk was reported by DMG along the southwest side of Glenoaks Boulevard close to the 1971 rupture and compressional warp (Charles Real, 1994, personal communication) (Locality 7, Figure 1). We did not check this locality.

San Gabriel Fault. Northwest-trending cracks were observed near this fault at Bouquet Junction (Locality 8). Located mostly in fill and partly in alluvium, the cracks showed a suggestion of a few millimeters or less of right-lateral slip in the fill. The cracks formed a narrow zone about 125 m long. Several mapped traces of the fault also

Photo 4. Looking east on Landers Street where driveway pushed gutter southward under street paving about 25 cm due to compression at toe of lateral spread feature (Locality 3a, Figure 2). Also note buckled sidewalk at upper left.

were checked in the hills to the southeast, but only minor cracking with no measurable displacement was noted 3 km to the southeast. The latter was coincident with a Holocene-active trace.

Beacon and Weldon Faults. Minor shaking cracks were noted in a railroad cut across the Beacon Fault, but otherwise there was no indication of fault displacement on either fault (Locality 9).

Cracks near Highway I-5. Ken Cole of the California Department of Transportation (Caltrans) reported (personal communication, 2/7/94) that cracks reopened along a 1971 fault rupture on a ridge just east of I-5 (Locality 10). He described this as a bedding plane failure with a dip of 70°N and 2.5 cm of vertical offset (north side down). He thought the rupture may relate to ridgetop spreading (i.e. landsliding). A report by Caltrans (1994) shows the crack zone to be 40 m long and speculates it is due to landsliding. The report identifies other ground cracks in the vicinity, all of which are considered to be landslide-related.

Santa Susana Fault. An extensional crack was observed by Allan Barrows of DMG on 1/18/94 in a dirt road where it crosses the Santa Susana Fault in a tributary to Aliso Canyon (Locality 11a). This feature was no longer visible at the time of follow-up studies in early April. Other fault crossings were checked, including a site west of Interstate 5 that ruptured in 1971 (Locality 11b), at Devil Canyon (Locality 11c), and at Tapo and Gillibrand Canyons (Locality 11d), but no evidence of surface faulting was observed.

Northridge Hills Fault. Reconnaissance along this concealed fault zone, from Veterans Hospital on the east to Winnetka Avenue on the west, found no evidence of fault displacement (Locality 12). The Northridge Hills Fault is a blind, north-dipping reverse fault that has uplifted Pleistocene alluvium into a series of anticlinal warps (Shields, 1977; Dibblee, 1992a). A post-earthquake leveling survey along Reseda Boulevard by the City of Los Angeles' Bureau of Engineering suggests that since the prior survey in 1980 the warp above the Northridge Hills Fault may have grown by as much as 5-10 cm. This deformation may have been coseismic.

Brugher (Browns Canyon) Fault. A significant aftershock (M 5.0, 1/29/94) occurred near this fault at a shallow depth of 1 km (Locality 13), but subsequent field reconnaissance found no fault-like features along the fault trace. Some cracks were observed nearby along the margins of a steep ridge, but these were due to shaking.

Ground Cracks Not Associated With Known Faults

Ground cracks not associated with mapped faults were widespread and in most cases were readily attributable to lateral spreading, landsliding, and other shaking effects. Initial reports by some geologists suggested that some of these localities may have a possible fault origin. Subsequent mapping did not confirm a fault origin for any of these cracks. The most prominent rupture areas are described below.

Potrero Canyon. Extensional cracks occurred almost continuously along the south margin of Potrero Canyon for a distance of 3 km (Locality 14). Initial reports

Photo 5. Scarp along south margin of Potrero Canyon shows about 35 cm of vertical displacement; right-stepping cracks suggest component of left-lateral displacement. Ruptures are due to settlement and westward lateral spreading of young valley fill. Nearby sand boils (not shown) indicate that liquefaction occurred (Locality 14, Figure 1).

Photo 6. Moletrack in soil at base of bedrock slope initially suggested thrust faulting at south margin of Potrero Canyon, but trench reveals that soil and root-mat were merely uncoupled by shaking. No faults were identified in the trench (Locality 14, Figure 1)

suggested this might be primary faulting. These extensional cracks occurred in Holocene alluvium, had up to 35 cm of vertical displacement (valley side down), and locally had a right-stepping pattern (Photo 5). Extensional cracks on the north side of the valley showed up to 45 cm of vertical displacement (valley-side down) and a left-stepping pattern. Evidence from subsequent investigations suggests that the alluvium of Potrero Canyon settled significantly and laterally spread westward down-valley. Other extensional cracks in re-entrant drainages are consistent with this conclusion. The presence of sand boils in two places adjacent to the extensional cracks indicate liquefaction at a shallow depth.

Locally associated with the extensional cracks on the south margin of Potrero Canyon were small-scale moletrack features in soil at the base of several bedrock slopes. This initially suggested that north-directed thrusting may have occurred. However, trenches excavated for Newhall Land and Farming Company showed that the soil thrusts are superficial and did not penetrate into bedrock (Photo 6). Trench logging by the U.S. Geological Survey indicated that the extensional cracks were confined to alluvium, but that a previous ground failure event had occurred (Rymer and others, this volume). The intense shaking needed to produce the above features was also reflected by many nearby significant landslides as well as shattered soil on at least one ridgetop. Also see mapping and discussion in Stewart and others (1994).

Las Brisas Orchard. Early reconnaissance reports indicated a zone of significant ground rupture through an orchard at the mouth of Tapo Canyon. The orchard is on alluvium along the south margin of the Santa Clara River valley in Ventura County (Locality 15). This locality is on trend with and 5 km west of Potrero Canyon (where faulting was also initially suspected) and just south of the concealed trace of the Oak Ridge Fault. Follow-up mapping found the ruptures to be extensional and arcuate and to lie entirely within alluvial fan and terrace deposits, which led to the conclusion that the ground failure was the result of lateral spreading. Although no sand boils were observed and liquefaction has not been verified as a mechanism in this locality, the ranch foreman reported that the orchard had been heavily irrigated prior to the earthquake and that the ground was probably saturated. The most severe spreading occurred west of Tapo Canyon where a graben, bounded by scarps to 0.5 m high and perhaps up to 1 m deep developed. A standpipe within this lateral spread area remained stationary while the soil moved past it for an estimated distance of 20 cm, indicating that spreading was quite shallow.

Simi Valley Ruptures. Ground ruptures, conceivably related to the nearby Simi Fault 0.6 to 1 km to the north but far more likely to be related to shaking, were observed at three locations in the northwest portion of the Simi Valley (Locality 16a, b, c). Other ruptures in Simi Valley were clearly related to lateral spreading and settlement (see Barrows and others, 1994; and Barrows and others, this volume).

a. A 150 m-long east-west trending zone of cracks with up to 5 cm of extension extends under a house and backyard at 3305 Amarillo Drive, causing the house and pool to tilt downward to the north (Locality 16a). An adjacent pool to the west (3304 Waco Drive) also is tilted northward, as is another pool one block further west (3328 Greenville). Two lots to the north on Amarillo Drive a pool is tilted southward. The tilted pools help define a local east-west trending graben. The cracks, which are in older alluvium (Dibblee 1992b), appear to be caused by settlement and minor downslope movement to the south.
b. A north-trending zone of cracks offsets Travis Avenue just east of El Prado Street (Locality 16b). The sense of offset is right-lateral (maximum slip of 2.5 cm) with a down-to-the-east component (1 cm). Ruptures can be traced southward across the street and lawn, diverting to the west around a house foundation. The cracks are just west of a filled drainage in Holocene alluvium. To the east of the drainage a separate northeast-trending zone of cracks passes from the drainage ditch and just south of a house at 3025 Corpus Christie Avenue. The cracks show up to a few centimeters extension and minor right-lateral slip. All of these cracks appear to be related to local settlement.
c. A zone of northeast-trending cracks with up to 2.5 cm vertical and 2.5 cm right-lateral slip offsets Texas Avenue (Locality 16c). The cracks splay out to the northeast in older alluvium of Dibblee (1992b) and cannot be traced as far as Ladonia Street to the southwest.

Northridge Epicentral Area. Widespread pavement cracks were reported near the epicentral area by consulting geologists (Slosson and Associates and Jeffery Johnson, Inc.) who suggested they may be due to faulting (Locality 17). We were able to verify many of the cracks, but could not always verify the trends or continuity as recorded. Many other cracks not recorded by the consultants were observed by DMG and other geologists. It was our impression that the vast majority of cracks were superficial and largely confined to paving and other concrete structures. Many of the cracks appeared to be due to shaking which caused the paving and curb segments to uncouple, migrate and interact with each other. Most cracks were parallel or orthogonal to existing streets, buildings, underground utilities, and related structures. In a few places it was noted that the cracks

offset streets and adjacent curbs and sidewalks and clearly extended into the ground below. These ground cracks tended to be very discontinuous and non-systematic, suggesting they were not due to faulting.

The Northridge area is underlain by Holocene alluvium with a relatively high water table (less than 10 m deep) and was rated by Tinsley and others (1985) as having a medium to high potential for liquefaction. Although clear evidence of liquefaction has not been reported, there was evidence of lateral spreading and differential settlement between Tampa and Vanalden avenues just south of Parthenia Street (Locality 17a). The principal rupture zone trended N 20°W across Napa Street (opposite #19133), offsetting both curbs about 18 cm in a right-lateral sense. The fracture zone, which was 8-13 m wide, could be followed northward through a house (damaged) and a yard with diminishing offset to Bryant Street where the cracks splay-out. One fracture did cross Bryant Street in a north direction, passing between two apartment buildings and turning eastward behind the foundation of one of the buildings where 5 cm of extension was measured. These right-lateral and extensional cracks appear to define part of the western margin of a poorly defined lateral-spread feature that may have moved downslope (to the south). Other fractures possibly associated with this feature are: (1) A zone of minor, east-trending, extensional cracks in asphalt paving just north of Parthenia Street and on both sides of Vanalden Avenue and (2) a N 45°E-trending zone of cracks to the southwest in a vacant lot at the intersection of Malden Street and Beckford Avenue. This zone formed a graben 10 cm deep and could be followed for 75-100 m. (K.M. Cruikshank, 10/30/94). Possibly related is an east-trending fracture zone to the west with up to 15 cm of extension and a "sag" as reported on Tampa near Malden Street by geologic consultant Rachel Gulliver-Dunn (personal communication, 1994). We were unable to verify this latter feature when visited on 1/27/94 as the street was being repaired.

Additional ground ruptures that probably were due to settlement and/or incipient lateral spreading occurred at:

- Northridge Junior High School (Locality 17b); 50-75 m-wide zone of northwest-trending, extensional cracks in alluvium and asphalt paving could be followed for nearly 200 m. The cracks in asphalt and fill(?) appeared to divert around a school building.
- Cleveland High School (Locality 17c); 2.5 cm of settlement on north side of the gymnasium; about 4-5 cm of settlement at east end of building A 1-9; many other extensional and compressional cracks in paving around structures and adjacent streets appear to be superficial and shaking-related.
- Shopping center north of Roscoe Boulevard and west of Winnetka (Locality 17d); east-northeast-trending zone of extensional and some compressional cracks in asphalt paving, sidewalks, curbs, and concrete floor of Vons Market at least 300 m long; possible incipient lateral spreading and pavement uncoupling; no evidence of faulting.

RELATIONSHIP TO THE ALQUIST-PRIOLO ACT

The purpose of the Alquist-Priolo Earthquake Fault Zoning Act (AP Act) is to mitigate the hazard of surface fault rupture to structures for human occupancy. This is accomplished by identifying active faults and establishing regulatory zones for implementation by cities and counties. The criteria for establishing Earthquake Fault Zones (EFZs) are that a fault must (1) have evidence of Holocene activity and (2) be reasonably well-defined as a surface feature (Hart, 1994). Local jurisdictions must then require geologic investigations to determine the presence and locations of active faults for specified development projects and avoid siting structures directly astride such faults. Since fault rupture almost always occurs along pre-existing faults that were recently active, a key assumption is that the location of future surface rupture is predictable. Another assumption is that active faults are relatively narrow features that can be avoided.

Numerous ground cracks formed during the January 17 earthquake, but most of these were not related to faulting. Rupture did occur on the Mission Wells Fault, which was previously zoned (Locality 2, Figure 2). Although minor, rupture precisely followed and had the same sense of displacement as the previous rupture in 1971, demonstrating the efficacy of the existing Earthquake Fault Zone. Minor ground cracks also occurred on or near previously zoned traces of other faults (Localities 4, 8, and 10, Figure 1), although it is not clear that these cracks were fault-related.

The most significant fault rupture occurred as bedding-plane faults near Newhall (Locality 1) where no faults had been previously recognized. Trench exposures, however, clearly revealed an association between the ground ruptures and previously sheared beds, demonstrating multiple prior movements (see Treiman, this volume). Although the recurrence interval between events is unknown, we can confidently predict that surface faulting very likely will occur along the same fracture zones in the future. Thus, the flexural slip faults near Newhall meet our zoning criteria (Holocene active and well-defined) and are recommended for future zoning (CDMG, 1994).

The ground cracks in the Granada Hills provided another interesting opportunity to test the application of the AP Act. Superficially, some of the cracks at Locality 3a, Figure 2, appeared to be fault-like and to lie generally along the projected trend of the concealed Mission Hills Fault. In addition, the principal cracks are roughly on trend with and lie less than a kilometer west of the previously established EFZ for the Mission Wells Fault.

As mentioned above, two criteria must be met before an EFZ can be established. Clearly, the Granada Hills cracks are Holocene (they formed in 1994). But they are mostly not well-defined as surface features because cracking in some areas was widely distributed. Moreover, deep trenches excavated by others across the best-developed traces near Balboa Boulevard did not demonstrate any clear evidence of previous rupture, although the age of the alluvium is relatively young. A more basic question, however, needs to be answered: Are the Granada Hills cracks faults? In our opinion, the preponderance of evidence indicates that the Granada Hills cracks are the result of lateral spreading caused by intense shaking and are not faults (see discussion in previous section). This opinion is also shared by Hecker and others (this volume) who have studied the Granada Hills cracks in great detail.

Although lateral spreading may occur again in the same general area and may again constitute a ground rupture hazard to structures, there is no evidence to suggest that future ruptures will occur along the same fracture zones. So how can the hazard of distributed or unpredictable ground ruptures be mitigated? The answer is multifaceted. First it must be recognized that not all ground ruptures — whether caused by faulting, lateral spreading, landsliding, or other processes — can be avoided in advance. If the rupture zones are predictable and well-defined, the ground rupture hazard can be mitigated by avoidance. And most landslides can be stabilized to limit or eliminate ground failure under static conditions. But what about distributed rupture that occurs during earthquakes?

It was noted after the 1989 Loma Prieta and the 1992 Landers earthquakes that faults and other ground ruptures tended to be partly diverted around the foundations of houses — even those that were only minimally reinforced (Hart and others, 1990 and 1993; Murbach, 1994). Similarly, ground cracks from the Northridge earthquake also were observed to divert around structures (e.g., at Locality 17). In fact, there was a strong tendency for sidewalks and other concrete paving to uncouple from the ground in areas of ground cracking and to selectively break along joints and other lines of weakness.

These observations suggest that foundation design may be useful in reducing the effects of ground rupture to structures caused by earthquakes, particularly where rupture is relatively minor or distributed. Lazarte and others (1994) and Murbach (1994) have evaluated the relationship of ground ruptures to distressed structures at Landers and recommend that geotechnical and structural engineering methods be employed to reduce the effects of ground deformation where avoidance is not feasible. Such measures can be employed anywhere ground deformation is anticipated, either in or out of an EFZ. However, if a ground fracture is identified as an active fault, then the only mitigation method allowed under the AP Act is avoidance. As a result, it has been our policy to zone only faults that meet our zoning criteria. It is not the practice at DMG to zone landslide, lateral-spread, and other fault-like features under the AP Act unless they are coincidental with active faults that otherwise meet our zoning criteria.

CONCLUSIONS

Surface faulting from the January 17, 1994 Northridge earthquake was very limited with only two localities of documented faulting — one along a previously known fault and one instance of secondary rupture along a group of bedding-plane faults. Other types of ground cracks were widespread, and in some cases gave the initial impression of faulting. With the possible exception of minor triggered slip, the other ground ruptures are attributed to lateral spreading, settlement, liquefaction, landsliding, and other failures associated with shaking.

The approach to locating and assessing fault rupture was twofold. Known or suspected faults were checked for fault rupture and reports of suspected ground rupture reported by others were investigated. Wherever possible the field mapping and follow-up was coordinated with other scientists. The success of this approach underscores the value of the Clearinghouse and the need for all scientists involved in the post-earthquake studies to report or summarize their findings as they develop.

The effectiveness of the Alquist-Priolo Act and Earthquake Fault Zones was only slightly tested. One of the two fault rupture locations mapped precisely mimicked the Mission Wells Fault, which ruptured in 1971. The other rupture occurred as flexural slip on the flank of the Pico Anticline where no fault had been previously mapped. Trench exposures revealed a clear relationship between the ground ruptures and pre-existing bedding-plane faults. Thus, the assumption that fault rupture has a strong tendency to recur along existing faults is reaffirmed.

ACKNOWLEDGMENTS

We would like to acknowledge the efforts and contributions of the many geologists who were out in the field in the chaotic days after the earthquake. Within the Division of Mines and Geology we had the assistance of Allan Barrows, Mark DeLisle, Richard Greenwood, Pamela Irvine, Tim McCrink, Charles Real, and Dinah Shumway. Geologists from the U.S. Geological Survey (see Rymer and others and Hecker and others, this volume), Caltrans (Ken Cole), the Lawrence Berkeley Laboratory (Patrick Williams) and several consulting geologists (notably Slosson and Associates, Geosoils, Inc., Geomatrix, and Seward Engineering Geology, Inc.) also made significant contributions to the effort to locate and evaluate surface rupture. This paper was reviewed by C.J. Wills, whose comments are appreciated.

REFERENCES

Barrows, A.G., Kahle, J.E., Weber, F.H., Jr., Saul, R.B., and Morton, D.M., 1975, Surface effects map of the San Fernando earthquake area *in* Oakeshott, G.B., ed., San Fernando, California earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, pl. 3.

Barrows, A.G., Tan, S.S., and Irvine, P.J., 1994, Investigation of surface geologic effects and related land movements in the City of Simi Valley resulting from the Northridge earthquake of January 17, 1994: California Department of Conservation, Division of Mines and Geology Open-File Report OFR 94-09, 1 pl.

California Department of Transportation (Caltrans), 1994, Fault Evaluation for 5/14 Interchange reconstruction: Unpublished report, 6 p., 2 pl., dated 7/14/94.

California Division of Mines and Geology, 1979, Earthquake Fault Zones, San Fernando quadrangle, Revised Official Map of January 1, 1979

California Department of Conservation, Division of Mines and Geology, 1994, Earthquake Fault Zones, Newhall quadrangle — Preliminary Review Map of December 1, 1994 (proposed revision of Official Map).

Dibblee, T.W., Jr., 1991, Geologic map of the San Fernando and Van Nuys (north 1/2) quadrangles, Los Angeles County, California: Dibblee Geological Foundation Map DF-33, 1:24,000.

Dibblee, T.W., Jr., 1992a, Geologic map of the Oat Mountain and Canoga Park (north 1/2) quadrangles, Los Angeles County, California: Dibblee Geological Foundation Map DF-36, 1:24,000.

Dibblee, T.W., Jr., 1992b, Geologic map of the Santa Susana quadrangle, Ventura and Los Angeles Counties, California: Dibblee Geological Foundation Map DF-38, 1:24,000.

Hart, E.W., Bryant, W.A., and Treiman, J.A., 1993, Surface faulting associated with the June 1992 Landers earthquake, California: California Geology, v. 46, n. 1, p. 10-16.

Hart, E.W., Bryant, W.A., Wills, C.W., and Treiman, J.A., 1990, The search for fault rupture and significance of ridgetop fissures, Santa Cruz Mountains, California *in* McNutt, S.R., and Sydnor, R.H., eds., The Loma Prieta (Santa Cruz Mountains), California earthquake of 17 October 1989: California Department of Conservation, Division of Mines and Geology Special Publication 104, p. 83-94.

Hart, E.W., 1994, Fault-rupture hazard zones in California: California Department of Conservation, Division of Mines and Geology Special Publication 42, Revised 1994, 34p.

Lazarte, C.A., Bray, J.A., Johnson, A.M., and Lemmer, R.E., 1994, Surface breakage of the 1992 Landers earthquake and its effect on structures: Bulletin of the Seismological Society of America, v. 84, p. 547-561.

Murbach, D., 1994, Characteristics of the 1992 fault rupture adjacent to distressed structures, Landers, California: Earthquake Engineering Research Institute, 73 p., and Appendix.

O'Rourke, T.D., and Palmer, M.C., 1994, The Northridge, California earthquake of January 17, 1994 — Performance of gas transmission pipelines: National Center for Earthquake Engineering Research, Technical Report NCEER-94-0011, 5 chapters.

Shields, K.E., 1977, Structure of the northwestern margin of the San Fernando Valley, Los Angeles County, California: Unpublished MS Thesis, Ohio University, 82 p., 13 pls.

Stewart, J.P., Thomas, P., Gookin, W.B., Seed, R.B., and Bray, J.D., 1994, Ground failure in Preliminary report on the principal geotechnical aspects of the January 17, 1994, Northridge earthquake: Earthquake Engineering Research Center, University of California, Berkeley Report No. UCB/EERC-94/08, 230 p.

Tinsley, J.C., Youd, T.L., Perkins, D.M., and Chen, A.T.F., 1985, Evaluating liquefaction potential *in* J.L. Ziony, ed., Evaluating earthquake hazards in the Los Angeles region — an earth-science perspective: U.S. Geological Survey Professional Paper 1360, p. 263-315.

U.S. Geological Survey and Southern California Earthquake Center, 1994, The magnitude 6.7 Northridge, California, earthquake of 17 January 1994: Science, v. 266, p. 389-397.

Wald, D.J., and Heaton, T.H., 1994, A dislocation model of the 1994 Northridge, California, earthquake determined from strong ground motions: U.S. Geological Survey Open-File Report 94-278, 54p.

Weber, F.H., Jr., 1975, Surface effects and related geology of the San Fernando earthquake in the Sylmar area *in* Oakeshott, G.B., ed., San Fernando, California, Earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, p.71-96.

Yeats, R.S., Huftile, G.J., and Stitt, L.T., 1994, Late Cenozoic tectonics of the East Ventura Basin, Transverse Ranges, California: American Association of Petroleum Geologists Bulletin, v.78, no.7, p.1040-1074.

Treiman, J.A., 1995, Surface faulting near Santa Clarita *in* Woods, Mary C., and Seiple, W. Ray., eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 103-110.

SURFACE FAULTING NEAR SANTA CLARITA

by

Jerome A. Treiman[1]

ABSTRACT

Secondary surface fault rupture accompanied the Northridge earthquake. As much as 19 cm of reverse bedding-plane slip was associated with up to 0.3 m of relative uplift. Some warping of the ground surface mirrored pre-existing subsurface structure. The fault rupture and uplift are attributed to compression and bending-moment faulting within the axial area of a northwest-trending concave-up monoclinal warp on the north limb of the Pico anticline.

INTRODUCTION

The Northridge earthquake produced no primary surface rupture that has been identified. Secondary ground-rupture, in the form of bedding-plane slip, has been found in a limited area of the Newhall 7.5-minute quadrangle on the north slope of the Santa Susana Mountains, approximately 20 km north of the epicenter (Treiman, 1994). The zone of fault rupture was about 250 m long with additional ground fracturing occurring for another 350 m to the north. This locality is near the mouth of Pico Canyon, west of the city of Santa Clarita (Figure 1).

SITE GEOLOGY AND GEOMORPHOLOGY

The geology of the area of faulting is simple (Treiman, 1986; Winterer and Durham, 1962). Interbedded sandstone and siltstone of the Pleistocene non-marine Saugus Formation is inclined to the northeast at 40° to 60°. This section of tilted strata lies within the north flank of the Pico anticline. The Saugus Formation is unconformably overlain by the flat-lying to gently northeast-dipping sands and gravelly sands of the late-Pleistocene Pacoima (?) Formation, a local fluvial and colluvial basin-fill deposit that is younger than 730,000 years (Treiman, 1982). Local unconformities have developed within the Pacoima (?) Formation in response to continued deformation. No faults had been previously identified in this area, although bedding-plane shears are common within the Saugus Formation in the Santa Clarita area. The nearest significant faults are the San Gabriel Fault (Holocene active) about 5 km to the northeast, the Holser Fault (Quaternary) about 5 km to the north, and the Santa Susana Fault (Quaternary) about 8 km to the south. The eastern end of the Santa Susana Fault had some minor displacement as a result of the 1971 San Fernando earthquake.

The area of rupture is along a northwest-trending strike-ridge. Several small spurs and drainages trend northeast from this ridgeline. The southern part of this ridge has been modified in recent years by grading for residential development. Prior to grading the most notable geomorphic feature was a naturally occurring northwest-oriented closed depression on the northeast side of the strike ridge. Most of this feature still exists north of the residential development, part having been removed by grading. The depression, about 70 m long and 40 m wide, lies between the main zone of faulting and a zone of discontinuous ground cracks to the north (Figure 2).

SEISMICITY

Prior to the Northridge earthquake the seismicity of the area had been dominated by aftershocks of the 1971 San Fernando earthquake. The Pico Canyon area was also heavily shaken by a significant pre-instrumental earthquake (the Pico Canyon earthquake) which occurred on April 4, 1893 (cited by Richter, 1973). No fault rupture was specifically reported from the 1893 event, although widespread rockfall and fissuring were recorded.

[1]California Department of Conservation, Division of Mines and Geology, Southern California Regional Office, Los Angeles, California

Seismicity from the Northridge earthquake defines a deep (19 km to 6 km), south-dipping (≈40°) thrust fault with scattered shallower aftershocks in the upper block (Hauksson and others, 1994). Although there is no apparent association of epicenters with the observed surface faulting, the rupture area is near the northern margin of an area that is more densely populated with epicenters. This may indicate a relatively abrupt change in the degree of deformation from south to north. It is not expected that significant seismicity would be spatially related to the type of relatively shallow ground rupture that is the subject of this report. Bedding-plane faulting of this nature is secondary to the main seismogenic fault displacement at depth.

GROUND EFFECTS OF THE EARTHQUAKE

The recent surface faulting is primarily within an area graded for development west of Interstate 5 (see Figure 2). Slip occurred along at least five bedding planes exposed in the building pads and cut slopes of the development (no structures had yet been built on the affected lots). Most displacement was concentrated in two principal zones, western and eastern. Fault displacement was consistently northeast-side up (up to 19 cm vertical separation) and lateral separations varied from about 4 cm right-lateral to 7 cm left-lateral. The individual ruptures were clearly compressional in nature and were expressed by a rounded southwest-facing scarp, commonly with a tensional fracture along the upper margin where the scarp was collapsing (photos 1 and 2). This morphology is in contrast to the more common open cracks and fissures, in this and other developments, that were clearly tensional. Post-earthquake trenching of the bedding-plane faults, by various consultants (Geosoils, 1995; Allan Seward, 1995a,b,c) has documented that the displacement occurred along bedding planes within clayey beds 2-18 inches (5 cm to 45 cm) thick.

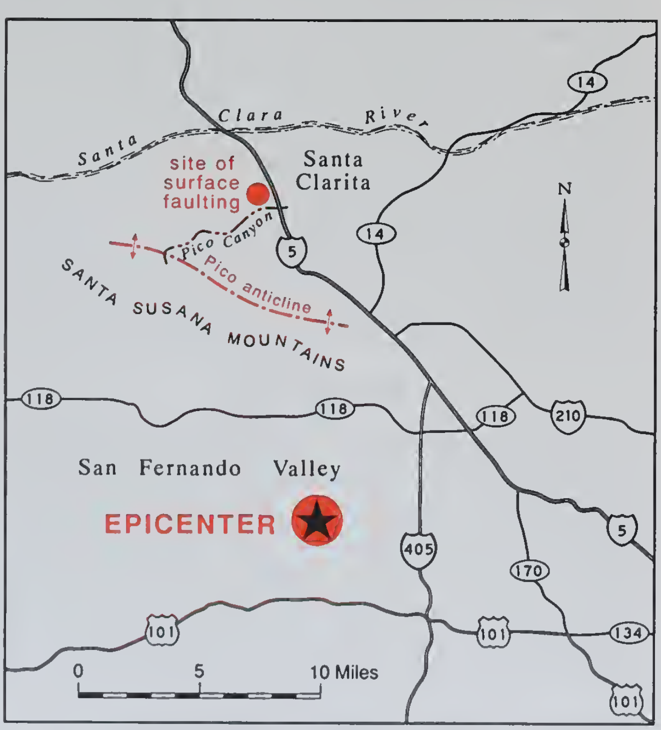


Figure 1. Location of the area of surface faulting near Santa Clarita.

The most continuous rupture (western zone) extended for about 250 m with a general trend of N40°W (photo 3). A post-earthquake survey for the landowner has documented at least 0.4-0.5 feet (12-15 cm) of vertical displacement (northeast side up) along the main rupture. [19 cm vertical displacement was measured by the author based on visual sighting across the scarp with a tape and is slightly at odds with the post-earthquake survey data. The visual measurement may have been skewed by the original slope of the graded pad, or may reflect ground warping not evident in the survey data]. Trenches across the rupture document a strongly developed bedding-plane shear zone dipping 50°-56°NE and associated with a thick (up to 0.5 m) claystone unit. Smaller parallel ruptures lay approximately 40-80 m to the northeast. One short 2 cm-high scarplet was also observed about 50 m to the west.

Bedding-plane displacement along the eastern zone was less prominent, but significant warping associated with this zone occurred across Holmes Place and to the southeast. At Holmes Place the road and curb were monoclinally warped down to the northeast (about 15 cm across a zone about 6 m wide), even though individual surface breaks showed the reverse sense of displacement (southwest side down) in the bedrock cut areas to either side of the road. Compression was indicated by shortening of the sidewalk and curb. The surface faulting and warping are associated with strongly deformed Pacoima (?) Formation (Trench DC-4, see Figure 3). These older alluvial deposits are folded and faulted across a relatively narrow zone (less than 8 m). Bedding within the Pacoima (?) Formation is locally overturned. In addition to the northeast-dipping bedding-parallel shears, the rocks have been displaced in the past by multiple southwest-dipping thrust faults. Near Holmes Place these thrusts appear to be displaced by the recent rupture. However, in trenches to the southeast, near Fitzgerald Avenue, shears associated with some of the 1994 surface rupture are offset at shallow depth along these older appearing (cemented) southwest-dipping shear zones. Warping across Fitzgerald Avenue was similar in magnitude but was broader (at least 20 cm vertical across a 25 m-wide zone). The sense of folding and faulting of bedrock (pre-1994) is consistent with surface warp-

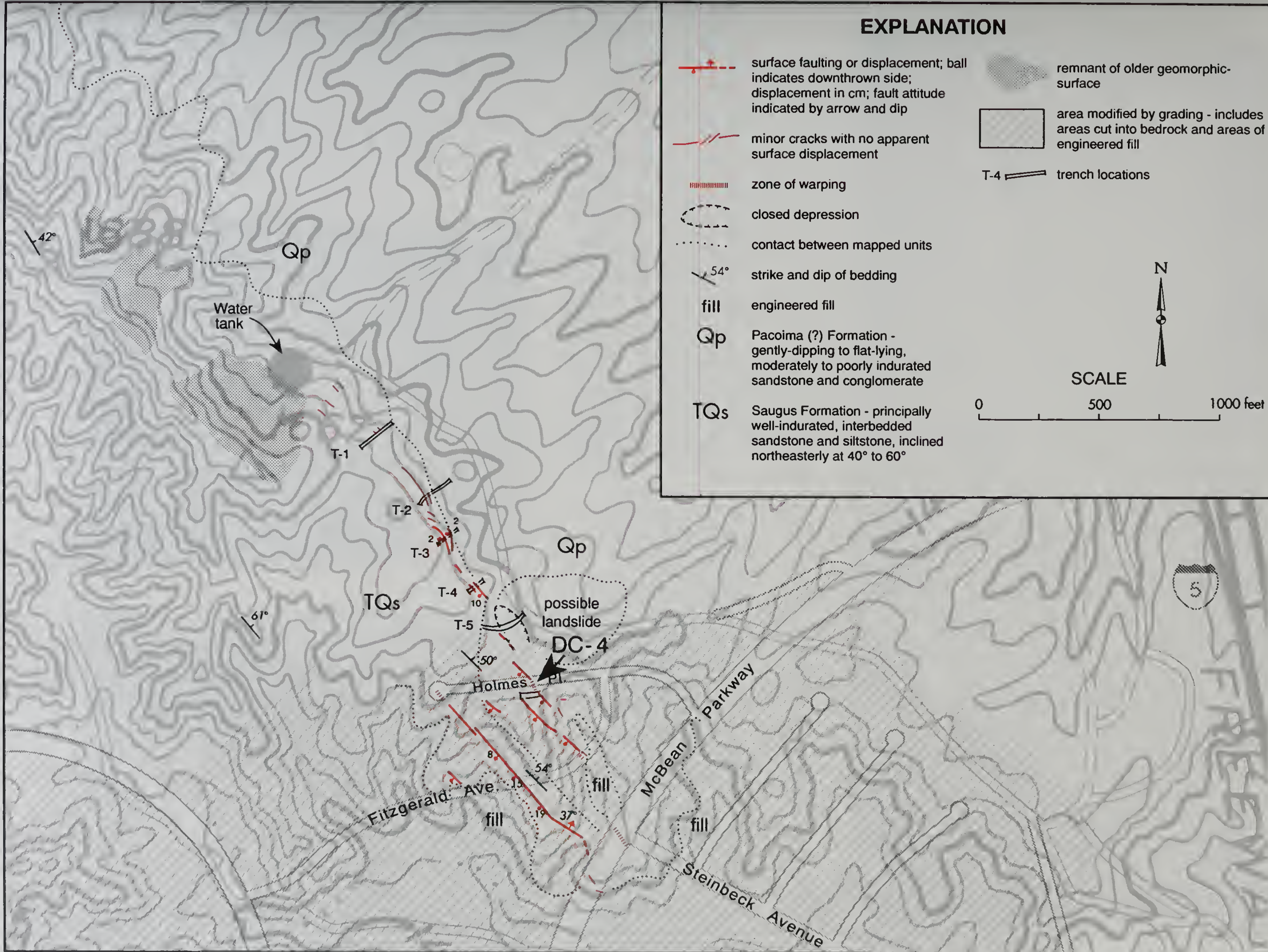


Figure 2. Bedding-plane faulting and related cracks, resulting from the Northridge earthquake, north of McBean Parkway, west of Santa Clarita.

Photo 1. Stereo-pair shows northerly view of 8 cm scarp along thrust fault. Photo by J. Treiman.

ing that occurred in 1994. The eastern rupture zone was traceable part way up a cut slope at the northern margin of the development. A post-earthquake leveling survey by Geosoils (1995) shows that the block between the western rupture zone and the eastern warp has been uplifted nearly one foot (30 cm), with relatively little internal deformation (Figure 4).

To the southeast the fault zone may continue across McBean Parkway. Cracking of the road and a subtle left-lateral displacement (2.5-3 inches; 6-8 cm) of the median along the Parkway align with the western rupture zone. This, however, is close to a cut/fill boundary. Along the projection of the eastern zone, at the intersection of McBean Parkway and Steinbeck Avenue, the Los Angeles County Engineering Department performed street repairs to correct a monoclinal warp in the road. Deformation here amounted to 6-8 inches (15-20 cm across a 20 m-wide zone) vertical uplift on the southwest (C. Nestle, L.A. County, personal communication). No surface fractures were noted at this locality. Farther to the southeast the zones of rupture either die out or are obscured by man-made fill. Minor ground cracks southeast of McBean Parkway appear to be more closely related to the margin of the

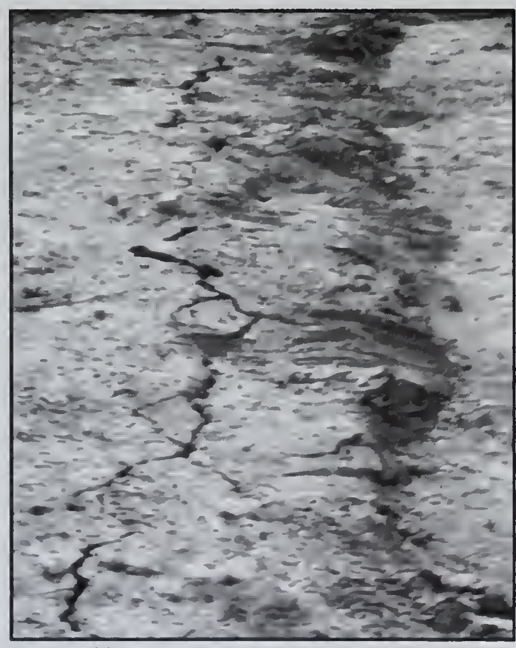


Photo 2. View southeast along the main rupture zone showing southwest-facing scarp. Note the tensional fracture which was typical along the thrust front. Photo by D. Sherman

Photo 3. View southeast along the most prominent rupture zone. Photo by D. Sherman.

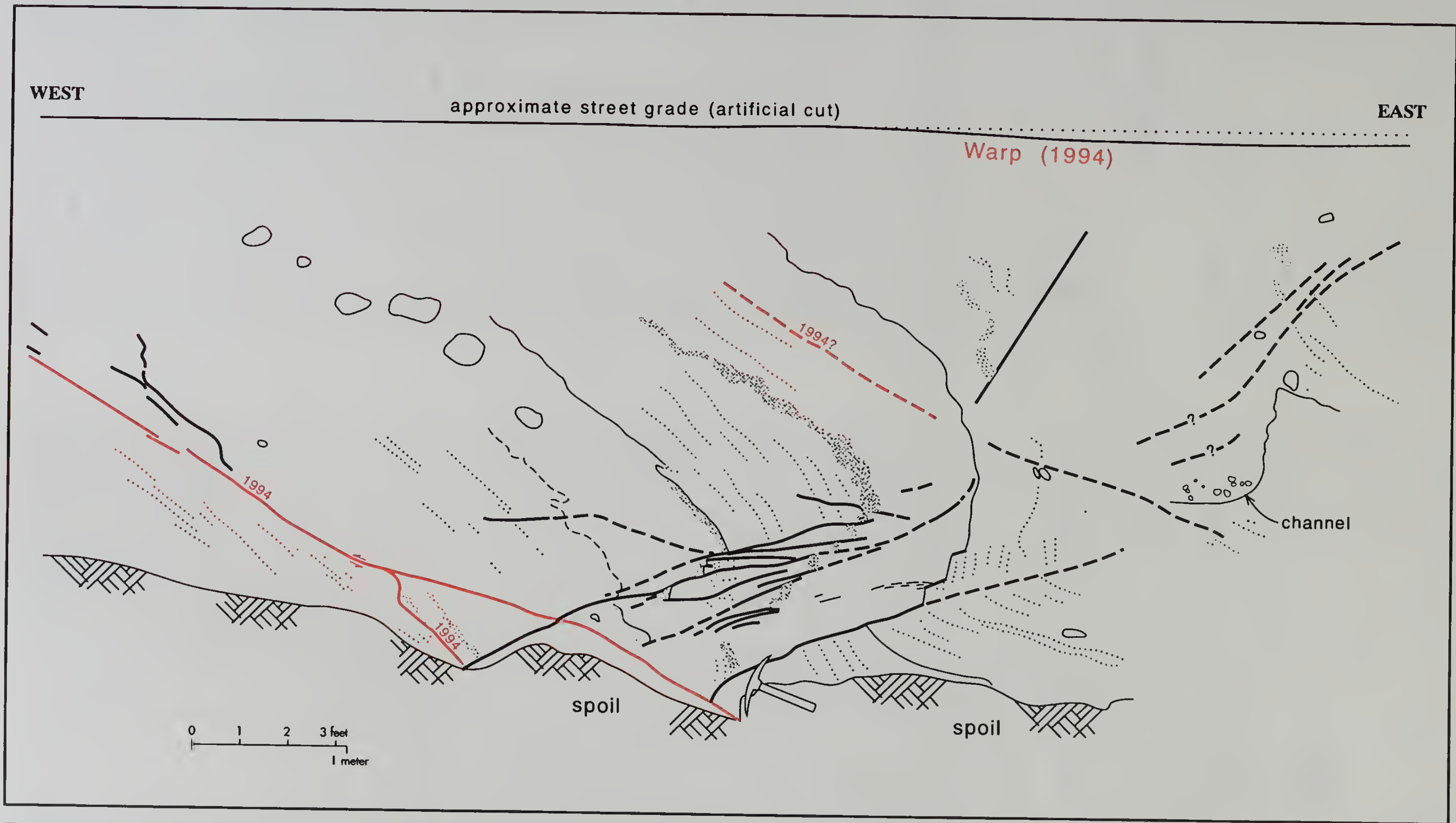


Figure 3. Sketch log of trench exposure (DC-4) south of Holmes Place. North wall of trench is shown. Trench depth is approximately 3.5 m below street level. Bedrock is Pacoima (?) Formation. Multiple low-angle thrust faults document a history of previous displacements that have folded the coarse sediments of the Pacoima (?) Formation. 1994 rupture surface, in the left portion of this sketch, offsets the southwest-dipping thrust surfaces. Rupture follows bedding-planes up to the left, from 2.5 m depth to the surface. Surface warping in 1994 mirrored the older folding and was probably accompanied by incremental growth of this structure (drawn from a 35mm slide).

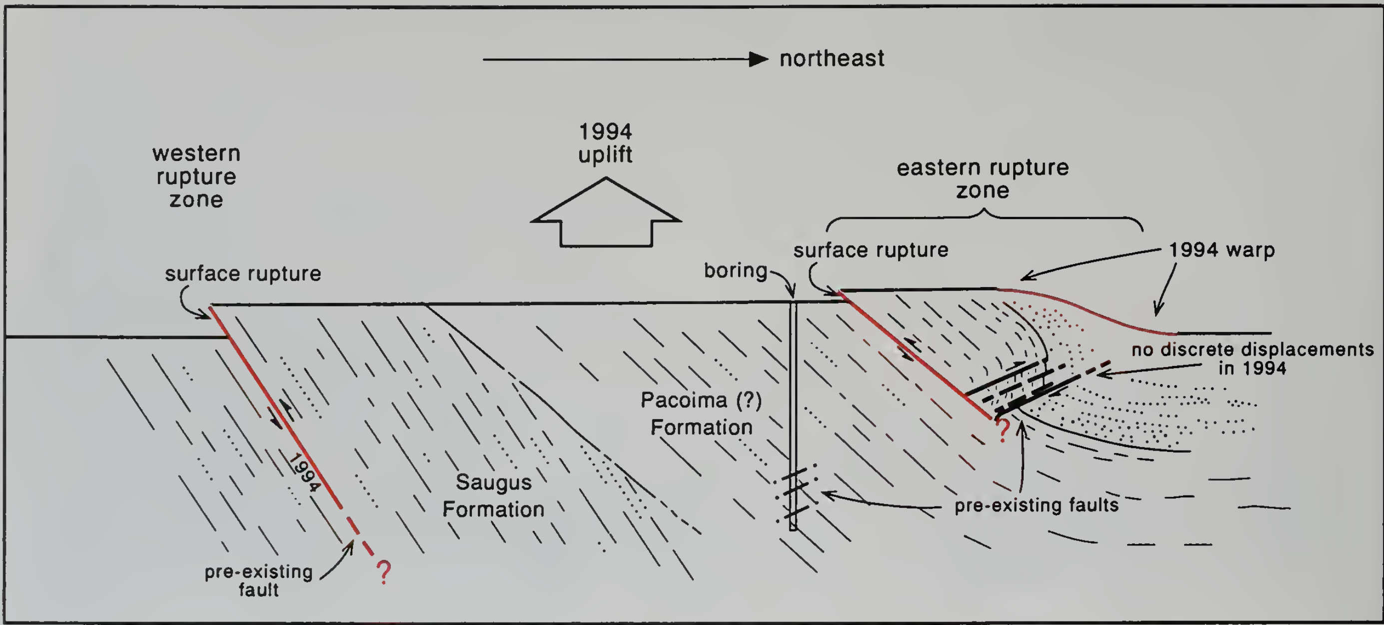


Figure 4. Cartoon summarizing the sense of displacement in the area south of Holmes Place (amount of slip is exaggerated). Section is looking northwest, along strike of bedding. Subsurface interpretation is based on surface mapping, trench DC-4 (shown in Figure 3), and unpublished consultants data (personal communication from D. Sherman and A. Seward).

compacted fill than to the trend of faulting. Possible fault displacement cannot be differentiated from the effects of fill settlement and shaking cracks in this area.

North of the development, within the closed depression, surface fracturing was not prominent. Several traverses across this depression found only a few discontinuous fractures in the soil along the southwest side and at the southern end, but none with any measurable vertical displacement. A large bulldozer and backhoe excavation by Seward (1995a; T-5) revealed gently to moderately northeast-dipping Pacoima (?) Formation with numerous fractures and shears. These included both northeast and southwest dipping reverse faults. Abrupt steepening of the bedding (similar to that shown in Figure 3) occurred in conjunction with southwest dipping thrust faults. None of the bedrock shears could be shown to have moved in the recent earthquake. A thick lens of overlying colluvial soil contained one southwest dipping fracture that resulted from the earthquake, however it was not traced downward into the bedrock. The closed depression, originally suspected to be of tectonic origin (Treiman, 1994), appears to be a segment of an old drainage that has been translocated by landsliding.

A N35°W trend of open soil fractures was found to continue from the northwest end of the closed depression. The fracture zone was best expressed as it crossed the northeast-trending spurs (extending from the strike-ridge) but was also traceable through part of the intervening canyons. For about 100 m the fracture zone was expressed intermittently by one to two uphill facing scarplets, from 2 cm to 10 cm high. Minor, discontinuous cracking across spur ridges was observable for another 200 m to the northwest. These latter cracks dipped southwest at the surface (in the soil), normal to the ground surface and appeared to be extensional. They had no measurable vertical displacement.

Four deep trenches excavated by Seward (1995a; see Figure 2) found most of the surface cracks north of the depression to be related to southwest dipping, slope-normal fractures that cut across bedding planes and died out in bedrock at a few meters depth. Up to 2 cm of normal displacement (northeast side up) was observed across these fractures within the trenches. In at least one trench (T-4 and possibly T-3) the southwest-dipping fracture veered downdip into bedding at a depth of about 4 m. Older bedding-plane shears were evident in many of the trench exposures. T-2 demonstrated the late-Quaternary folding of the Pacoima (?) Formation, where the bedding changed from an inclination of 37°NE to horizontal within a distance downdip of about 13 m. The contact between the Pacoima (?) and Saugus formations was sheared (prior to the 1/17/94 earthquake). Shears were not as evident in T-1. The trenches also exposed older bedding-plane faults and southwest-dipping reverse faults in the bedrock. There was no direct evidence in the trenches of Holocene faulting, but neither did they entirely eliminate this possibility.

No cracks of a tectonic origin were visible at the site of a 4-million-gallon water tank immediately to the northwest of the last fractures or farther to the northwest. A careful traverse was made for at least 500 m and a general reconnaissance along trend for another 2 km failed to find any cracking other than from shaking or landsliding.

Past deformation or uplift in the area to the northwest is suggested by several remnants of a gently-sloping geomorphic surface (Figure 2). The larger of these remnants has been modified by grading for and construction of a 4-million gallon water tank. A small colluvial-surface remnant is also partially preserved within one of the active drainages. These surfaces may have been accentuated by damming of slopewash deposits by reverse bedding-plane displacements or ridgetop settlement, or they may have been isolated and preserved by uplift along a fault or fold.

DISCUSSION

There is little question that faulting of a secondary nature occurred west of Santa Clarita during the Northridge earthquake. The observed features cannot be entirely explained by shaking. The zone of reverse bedding-plane faults in the southern (graded) part of the study area is compressional and was in clear contrast to extensional fractures observed elsewhere in the earthquake affected region. The simplest interpretation relates the faulting to the bending-moment within the axial region of a concave-up monoclinal warp (see right side of Figure 4). An alternate tectonic explanation calls on flexural slip associated with tightening of the Pico anticline. This interpretation is consistent with the uplift and compression of the Santa Susana Mountains as indicated by Global Positioning System data (Ken Hudnut, USGS, personal communication); however, such an effect might be expected to be more widespread than was observed in this event.

Apparent across the site is a northwest-trending concave-up monoclinal flexure. This fold was evident at Holmes Place (Figure 3) and in subsurface data to the north and south (Seward, 1995a,b,c). It appears to be the principal tectonic feature in this immediate area, and the various surface ruptures are interpreted to be a response to this folding. The complex of interrelated folding and reverse faulting revealed in the various post-earthquake studies (GeoSoils, 1995; Seward, 1995a,b,c) may be interpreted as bending-moment thrust faults and bedding-plane faults associated with the tightening of this fold (see Yeats, 1982a). The geologic record preserved in trench DC-4 (Figure 3) shows repeated past compressional folding and faulting that has continued to affect the youngest (late-Quaternary) geologic unit on site. The folding of the younger deposits was particularly well-illustrated just south of DC-4, where the dip of the bedding increased from horizontal to 50° within a distance of 30 feet (13 m). Figure 3 also demonstrates the narrow zone of overturned bedding associated with the cross-cutting reverse faults. Surface warping in 1994 mirrored this prior deformation. Late-Quaternary deformation was also evident in other excavations in the graded area as well as to the north in T-2, T-4 and T-5 (Seward, 1995a). The progressive folding and unconformities between the Saugus Formation (TQs) and overlying deposits also document the long-term activity of this zone of flexure.

With tightening of the fold it is natural that the axial region will be squeezed and forced upward and northeastward. This has resulted in the bending-moment thrust faults and small folds on the east as well as the bedding-plane back-thrusts to the west. The faults within this active fold may well be shallowly rooted and probably are not seismogenic. Bending-moment faults generally diminish in slip as they approach the zone of neutral stress within the fold. Nevertheless, fault rupture (and significant surface deformation) can be expected to recur in the future in this linear zone of flexure.

This zone of flexure may be the northeastern limit of tightening related to compression and uplift of the Santa Susana Mountains, or merely a locally active fold axis near the margin of the Santa Susana Mountains anticlinorium. It may also be a fault propagation fold related to an unmapped thrust fault at depth or possibly even the tip of the Northridge event.

Explanations besides bending-moment faulting and flexural slip were also considered for the faulting. Seismically triggered bedrock rebound due to removal of overburden has been suggested (GeoSoils, 1995; Seward, 1995a,b,c). However, although as much as 70-80 feet of bedrock was removed from above the area of uplift (in 1987), comparable or greater removals elsewhere in the tract were not accompanied by surface faulting. If uplift were due to elastic rebound it should have occurred as well in other larger cuts in the development. Instead uplift was restricted to the axial area of a well defined monoclinal warp. The nature of the deformation indicates that uplift of the site was a response to horizontal shortening.

Trenching on the property to the north (Seward, 1995a) has shown the continuation of the zone of late-Pleistocene folding and compression, although the 1994 surface fractures could not be observed to be directly related to faulting at depth and had no clear evidence of prior movements. Although the recent surface fracturing in this zone is perhaps more simply explained as a shaking phenomenon than as a tectonic one, its correspondence to the zone of folding is remarkable. The active flexure is probably the underlying cause of the outwardly tensional surface fracturing. This association is supported by the linear *en echelon* nature of the fracture zone. Figure 5 illustrates how normal faulting may occur in association with bending-moment thrust faulting. These normal displacements may also be at least partly enhanced by ridgetop spreading and downslope movement associated with shaking. Preserved rem-

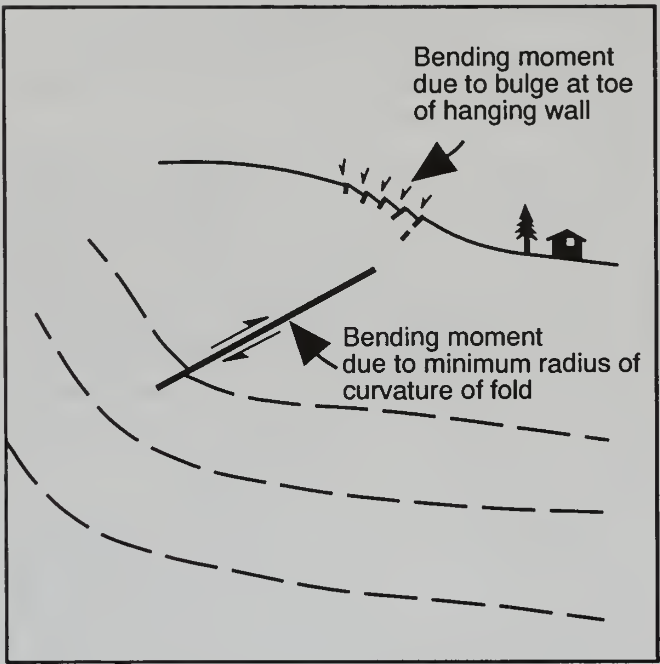


Figure 5. Illustration of bending-moment thrust fault and related normal faults (modified from Yeats, 1982b, Figure 2).

nants of an older geomorphic surface to the northwest (discussed in the previous section) are suggestive of previous deformation, but are not compelling.

CONCLUSIONS

Surface and subsurface investigations have demonstrated that the 1994 reverse surface displacements were associated with previously sheared bedding planes. The subsurface investigations also revealed pre-existing southwest dipping reverse faults (for which 1994 displacement was possible but not demonstrable) and evidence of ongoing Quaternary folding. Two types of folding were evident: a broader concave-up monoclinal fold of the Saugus and younger formations and smaller-scale drag folding associated with the southwest-dipping reverse faults within the younger units in the axis of the monoclinal fold. Folding of this latter type was mirrored by 1994 ground deformation.

The zone of reverse bedding-plane faults in the study area is compressional and was in clear contrast to extensional fractures observed elsewhere in the earthquake affected region. The surface faulting, fracturing and deformation are interpreted to be the result of bending-moment faulting along a hingeline at the northern margin of tilting associated with tightening of the Pico anticline.

ACKNOWLEDGMENTS

I thank Earl W. Hart and Christopher Wills, Division of Mines and Geology geologists, for their technical review of this article. Dave Sherman and Allan Seward generously shared data from ongoing investigations. This study would not have been possible without the cooperation of Dale Poe Development Corporation and Newhall Land and Farming Company.

REFERENCES

GeoSoils, Inc., 1995, Earthquake effects on undeveloped lots in the area of Holmes Place and Fitzgerald Avenue, Tract 33698, Stevenson Ranch, California: unpublished consultants report, W.O.2155-W-VN, February 27, 1995.

Hauksson, E., Hutton, K., Kanamori, H., Jones, L., and Mori, J., 1994, The M6.7 Northridge, California, earthquake of January 17, 1994 and its aftershocks (abstract): Seismological Society of America, 89th Annual Meeting, Program for Northridge Abstracts, abstract 4.

Richter, C.F., 1973, Historical seismicity of San Fernando earthquake area *in* San Fernando, California, Earthquake of February 9, 1971: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C., v.III, p.1-11.

Seward, Allan E., Engineering Geology, Inc., 1995a, Geologic report - earthquake distress, vesting tentative tract 45433 and vicinity, Westridge Project, Valencia, California: unpublished consultants report, Job No. 95-787EQ, February 6, 1995, 2 vol.

Seward, Allan E., Engineering Geology, Inc., 1995b, Geologic report - earthquake distress, Marblehead Condominiums, tract 44338, Pico Canyon, California: unpublished consultants report, Job No. 95-1477-9, February 6, 1995, 2 vol.

Seward, Allan E., Engineering Geology, Inc., 1995c, Geologic report - earthquake distress, Stevenson Ranch and vicinity, tract 33698, Pico Canyon, California: unpublished consultants report, Job No. 95-1490-9, February 6, 1995, 2 vol.

Treiman, J.A., 1982, Age of upper Saugus Formation at Newhall, California and implications as to the age of the Santa Susana Mountains *in* Fife, D.L. and Minch, J.A., editors, Geology and mineral wealth of the California Transverse Ranges: South Coast Geological Society, Santa Ana, California, p. 330.

Treiman, J.A., 1986, Landslide hazards in the west half of the Newhall quadrangle, Los Angeles County, California: California Division of Mines and Geology, Open-File Report OFR 86-6LA, 1:24,000.

Treiman, J.A., 1994, Bedding-plane slip associated with the 17 January 1994 Northridge earthquake (abstract): Seismological Society of America, 89th Annual Meeting, Program for Northridge Abstracts, abstract 34.

Winterer, E.L., and Durham, D.L., 1962, Geology of southeastern Ventura basin, Los Angeles County, California: U.S. Geological Survey Professional Paper 334-H, p. 275-366.

Yeats, R.S., 1982a, Low-shake faults of the Ventura basin, California *in* Cooper, J.D., comp., Neotectonics in southern California, volume and guidebook: Geological Society of America, 78th Annual Meeting, p. 3-15.

Yeats, R.S., 1982b, Reply *in* Cooper, J.D., comp., Neotectonics in southern California, volume and guidebook: Geological Society of America, 78th Annual Meeting, p. 21-23.

Hecker, S., Ponti, D.J., Garvin, C.D., and Hamilton, J.C., 1995, Characteristics and origin of ground deformation produced in Granada Hills and Mission Hills during the January 17, 1994 Northridge, California, earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 111-131.

CHARACTERISTICS AND ORIGIN OF GROUND DEFORMATION PRODUCED IN GRANADA HILLS AND MISSION HILLS DURING THE JANUARY 17, 1994 NORTHRIDGE, CALIFORNIA, EARTHQUAKE

by

Suzanne Hecker[1], Daniel J. Ponti[1],
Cristofer D. Garvin[1], and John C. Hamilton[1]

ABSTRACT

The M 6.7 Northridge earthquake of January 17, 1994 produced concentrated ground deformation and associated damage in a 5-km-long linear belt within suburban Granada Hills and Mission Hills in the northern San Fernando Valley. Small-displacement cracks comprise discrete zones with characteristics that reflect control by local physiographic and near-surface conditions. Several semi-arcuate zones of tension cracks and a zone of compression (expressed as crumpled pipelines and crushed pavement) formed in Holocene alluvium on the gently sloping piedmont west of Bull Canyon. Surveys of laterally and longitudinally deformed roads in the area show that the ground shifted downslope as much as 60 cm between the zones of ground extension and compression. However, little or no net deformation is observed across the ~500-meter breadth of the area. A trench exposure across a major zone of tension cracks shows downward-decreasing vertical displacements, perhaps attributable to differential compaction of the young, loose sediment. These sets of observations point to shallow mass movement, perhaps in conjunction with compaction, as the cause of deformation in the area west of Bull Canyon. A combination of tension cracks and compressional buckles developed along the pre-development course of Bull Creek in lower Bull Canyon and above filled tributary drainages farther east. The relation of this deformation to stream channels and, locally, to small sand boils implicates liquefaction, sediment compaction, and/or lurching of surficial deposits as the likely cause(s) of deformation. Tension cracks also developed on the moderately steep flank of the Mission Hills anticline at the east end of the deformation belt. Locally, these features are clearly related to slope failure, but cracks in the largest set also follow downslope-dipping bedding and thus could be an expression of slip accommodation related to possible coseismic folding in the anticline.

The various characteristics of deformation in the Granada Hills–Mission Hills belt are consistent with one or more types of shallow-seated phenomena (i.e., slope failure, sediment compaction, sediment lurching, or liquefaction) and are largely not consistent with a tectonic faulting origin. The nature of these phenomena implicates strong ground shaking as a primary driving mechanism for deformation. The concealed Mission Hills reverse fault projects to the surface along the length of the belt and may have indirectly triggered the surficial ground failures, either by focusing or generating seismic energy, or by causing movement within the overlying anticline.

The distribution of ground deformation strongly reflects the distribution of damage (to roads, utility lines, and structures) in the Granada Hills–Mission Hills area. This correlation points to the value of understanding factors that control the location of shaking-induced ground failures (such as position above concealed thrust faults), as well as the frequency at which these failures occur. Preliminary trench evidence from the west end of the deformation belt suggests that ground failure here may be a relatively uncommon (~10^3 yr?) event. Understanding the risk posed by this hazard requires more work, however, both locally, to better establish recurrence times, and regionally, to identify the extent of the hazard.

[1]U.S. Geological Survey, Menlo Park, California

INTRODUCTION

The M 6.7 Northridge earthquake was the largest earthquake to strike the Los Angeles metropolitan region in 23 years and produced an estimated $20 billion in direct economic losses (Goltz, 1994). Most of the damage to buildings and infrastructure in the region can be attributed to the effects of strong ground shaking, but damage in Granada Hills and Mission Hills, located approximately 10 km northeast of the epicenter in the northern San Fernando Valley, is largely associated with permanent ground deformation (Figure 1). Ground cracks with movement in the centimeter to decimeter range displaced the foundations of houses, fractured swimming pools, broke apart sidewalks and streets, and ruptured utility lines within a belt ~5 km long and several hundred meters wide. The deformation was concentrated in certain areas within the belt and formed locally complex associations of ground and pavement cracks, graben, compressional features such as buckled pavement and tented sidewalks, and lateral offsets of sidewalks and curbs.

Immediately following the earthquake, the U.S. Geological Survey deployed a team of geologists from Menlo Park to the San Fernando Valley to search for and document possible surface faulting. The results of our initial reconnaissance, along with the preliminary seismic and geodetic data for the earthquake, clearly indicated that the Granada Hills–Mission Hills deformation belt was not the result of surface faulting on the source fault of the earthquake. However, the belt does exhibit some general characteristics suggestive of sympathetic movement or triggered slip. Principal among these are the belt's position both in the hanging-wall of the causative fault and along or near surface projections of the Mission Hills Fault Zone and anticline.

Of the three major earthquakes to have struck onshore California in the last five years (1989 Loma Prieta, 1992 Landers, and 1994 Northridge), only one, the strike-slip Landers event, produced clear evidence of primary surface faulting. The other two earthquakes occurred on concealed thrust or oblique-reverse faults, and, while rupture on the causative faults was not clearly expressed, both events produced varying amounts of surface deformation in the hanging wall (U.S. Geological Survey Staff, 1990; Hecker, and others, 1995). The origin of these types of secondary deformation has been variously attributed to tectonic faulting and/or shaking-induced ground failure, and is a subject of active scientific debate (Ponti and Wells, 1991; Johnson and Fleming, 1993).

To address the issue of whether the origin of deformation in the Granada Hills–Mission Hills area is secondary surface faulting or shaking-induced ground failure, we embarked upon a detailed field investigation of the area. In addition to determining the cause(s) of deformation, we sought to assess how the ground cracks relate to the widespread infrastructure and structural damage in the area, and to evaluate the predictability and recurrence behavior of the hazard. Between January 17 and mid-March of 1994, our field investigations involved ground-crack mapping at a scale of 1:1000, compilation of initial damage surveys, and detailed ground surveys to document the displacement field associated with the deformation (Hecker, and others, 1995). In late July of 1994, we began the first of several planned trenching investigations of the ground cracks. This report presents our observations and conclusions based on these initial studies.

GEOLOGIC SETTING

The Granada Hills–Mission Hills deformation belt trends east-west along the south flank of the Santa Susana Mountains (Figures 1 and 2). Ground cracks in most of the belt developed across a low-gradient (~2%) piedmont in fine-grained Holocene alluvium. Within the eastern third of the belt, cracks developed in Miocene and Pliocene marine sediments and Pleistocene alluvium on the steep southern flank of the Mission Hills anticline (Figure 2).

The deformation belt overlies the east-west-trending Mission Hills anticline and its buried equivalent to the west, and many of the ground cracks lie along possible surface projections of concealed north-dipping reverse faults within the Mission Hills Fault Zone (Figure 2). These structures have been inferred based on topographic evidence, subsurface oil well data, and seismic-reflection profiles (Barrows and others, 1975a; Shields, 1977; Dibblee and Ehrenspeck, 1991,1992; W. Bartling, unpublished data). The buried anticline apparently comes to the surface west of the study area, in the Santa Susana Mountains, as the Mission anticline (Shields, 1977).

The deformation belt nearly abuts, but is slightly south of, the western end of surface faulting produced by the 1971 San Fernando earthquake (Figure 2). The area of 1994 deformation experienced little surface disturbance during the 1971 earthquake, except for some minor cracks that were observed at several localities (Barrows and others, 1975b). The Northridge earthquake caused cracking to recur at or near most of these localities.

Figure 1. Map showing location of deformation in the Granada Hills–Mission Hills area produced by the January 17, 1994 Northridge earthquake. Cracks (dark lines) simplified from Hecker and others (1995). Also shown are the approximate locations of the strong motion site at the Rinaldi Receiving Station (triangle), and the epicenter of the M_L 5.9 aftershock that occurred about 1 minute following the main shock (star). Numbers refer to localities described in the text.

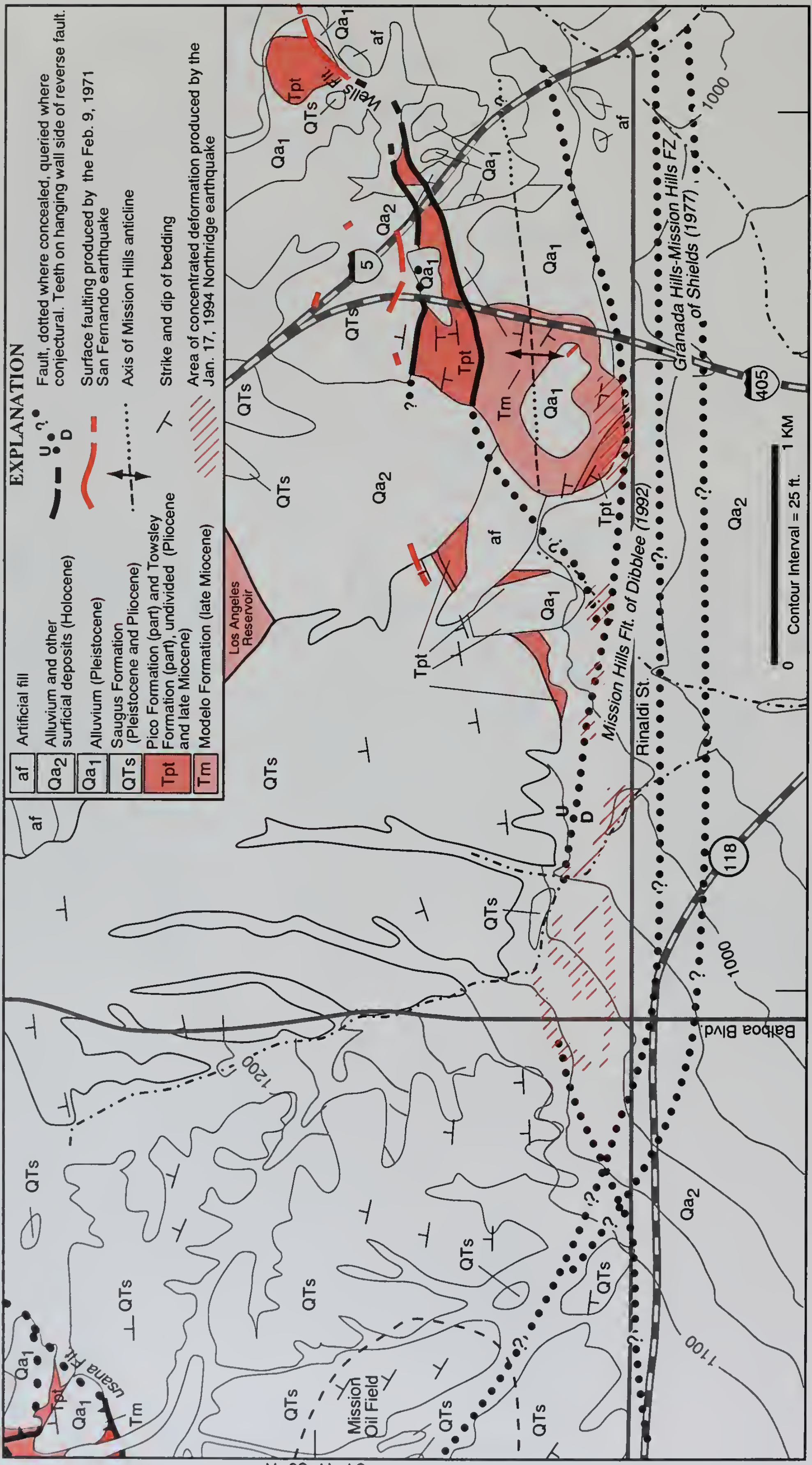


Figure 2. Simplified geologic map of the Granada Hills–Mission Hills area, showing the relation between concentrated zones of cracks produced in 1994 and geologic structure. Geology modified from Dibblee and Ehrenspeck (1991, 1992), Shields (1977), and Barrows and others (1975a). Topography from USGS Oat Mountain and San Fernando 7.5' quadrangles.

CHARACTERISTICS OF GROUND DEFORMATION

Deformation in the Granada Hills–Mission Hills area can be subdivided into (a) zones where deformation is concentrated and observable in bare ground and (b) intervening areas where deformation is more sparsely distributed and generally limited to surficial cracks in pavement (Figure 2). The physiographic setting and character of ground deformation in the zones vary across the broader belt of ground cracks; these aerial variations serve as the organizational basis for this section of the report.

West of Bull Canyon

The most intensive ground deformation and damage in the Granada Hills–Mission Hills belt occurred in a ~1-km-long by 0.5-km-wide area located west of Bull Canyon and north of Rinaldi Street (Figure 3). In addition to causing pavement and structural damage, ground cracking ruptured several buried utility lines beneath Balboa Blvd., including a 55 cm (22 inch) high-pressure natural gas main, a 15 cm (6 inch) natural gas distribution pipeline, and two water trunk lines (124 cm (49 inch) and 173 cm (68 inch) diameter) (O'Rourke and Palmer, 1994). Leaking gas ignited, and the ensuing fire destroyed five nearby houses and partially damaged a sixth (see Figure 3, locality 1a; Photo 1).

Map Data

Maps of cracks in the area west of Bull Canyon document several semi-arcuate subzones of dominantly extensional ground cracks that are consistent with south-

Photo 1. View to northwest of principal zone of tension cracks and one of five houses destroyed by fire on Balboa Blvd. (west of locality 1a, Figure 3). Tensile failure of gas lines beneath the street (to the right of view) led to the fire. Note large ground crack (arrow; see Photo 2), with southeast-side-down vertical separation, subsequently exposed in a trench excavated for this study. Photo by M.J. Rymer.

Photo 2. Close up view (to northwest) of large ground crack where it disappears beneath remnants of burnt house at 11661 Balboa Blvd. (Photo 1). Measurements from a trench at this site document 22 cm of southeast-side-down vertical separation at the ground surface. The crack was widened considerably by caving from surface flooding following rupture of nearby water mains. Photo by S. Hecker.

east-directed ground movement during the earthquake. The most prominent subzone of tension cracks locally reaches a width of 50 m and extends westward from Bull Creek to approximately Amestoy Ave. (Figure 3). This subzone crosses Balboa Blvd. (Photo 1) where the pipelines failed in tension. Less well defined subzones of tension cracks are observed in the area bounded by McClennan Ave., Rubio Ave., Armstead St., and Halsey St. (Figure 3). Individual ground cracks in these subzones are typically several meters long and rarely extend for more than a few tens of meters. The cracks trend mostly northeast to east-southeast and display a component of lateral slip that varies depending on the specific angular relation between their orientation and the ground-movement direction. Azimuths of horizontal vectors measured across individual ground cracks range from 130° to 170° (Hecker and others, 1995). This direction of movement is roughly parallel to the area's topographic gradient (Figure 2). Vertical displacements, where present, are generally down to the southeast. Amounts of vertical and horizontal displacement are rarely more than a few cm per crack, although some cracks display as much as 25 cm of vertical separation (Photo 2). Unlike the rest of the

Figure 3. Aerial photograph of the Bull Canyon area taken on the day of the earthquake, showing locations of cracks (dark lines) relative to cultural features and to damaged (tagged) structures (as reported to us by California Office of Emergency Services on 3/16/1994). Cracks from Hecker and others (1995); photo base courtesy of I. K. Curtis Services, Inc.

ground deformation west of Bull Canyon, tension cracks adjacent to Bull Creek indicate east- to northeast-directed movement that is normal to the stream cut and probably is the result of incipient slope failure toward the channel (Figure 3, locality 2).

A few hundred meters south of the subzones of extensional deformation lies an approximately east-west-trending subzone, coincident or on-line with Flanders St. (Figure 3), that contains a number of compressional features. The compression is generally expressed as tenting, buckling, and thrusting of concrete slabs and pavement (Photo 3), especially where walkways and driveways abut roads. Compression at the surface in bare ground is not noted (other than localized mounding of soil against slabs), but the earthquake did cause pipelines beneath Balboa Blvd. to be compressed ~25 cm within this subzone (O'Rourke and Palmer, 1994; Figure 3, locality 1b). Evidently, compressional stresses were sufficient to deform brittle surface layers and rigid buried pipelines, but were insufficient to create noticeable structures in bare ground where much of the displacement may have been absorbed within the soil.

The location and orientation of individual surface cracks in the area west of Bull Canyon, and in much of the Granada Hills–Mission Hills belt, are commonly controlled by cultural features, such as roads or houses. These features typically either deflected the ground cracks or broke apart as they decoupled from the underlying ground during seismic shaking. Decoupling and differential movement caused roads and other thin surface slabs to break apart over distances that are commonly broader than the adjacent zone of ground cracks (Figure 3). Slab decoupling may also explain the isolated occurrences of compressional features (such as tented and overlapped sections of sidewalks, popped curbs, and buckled pavement; Photo 3) within the zones of tension cracks, and points to the difficulty inherent in interpreting kinematic data from pavement breaks. Because of these complications, we measured crack-specific displacement vectors only on cracks in natural ground.

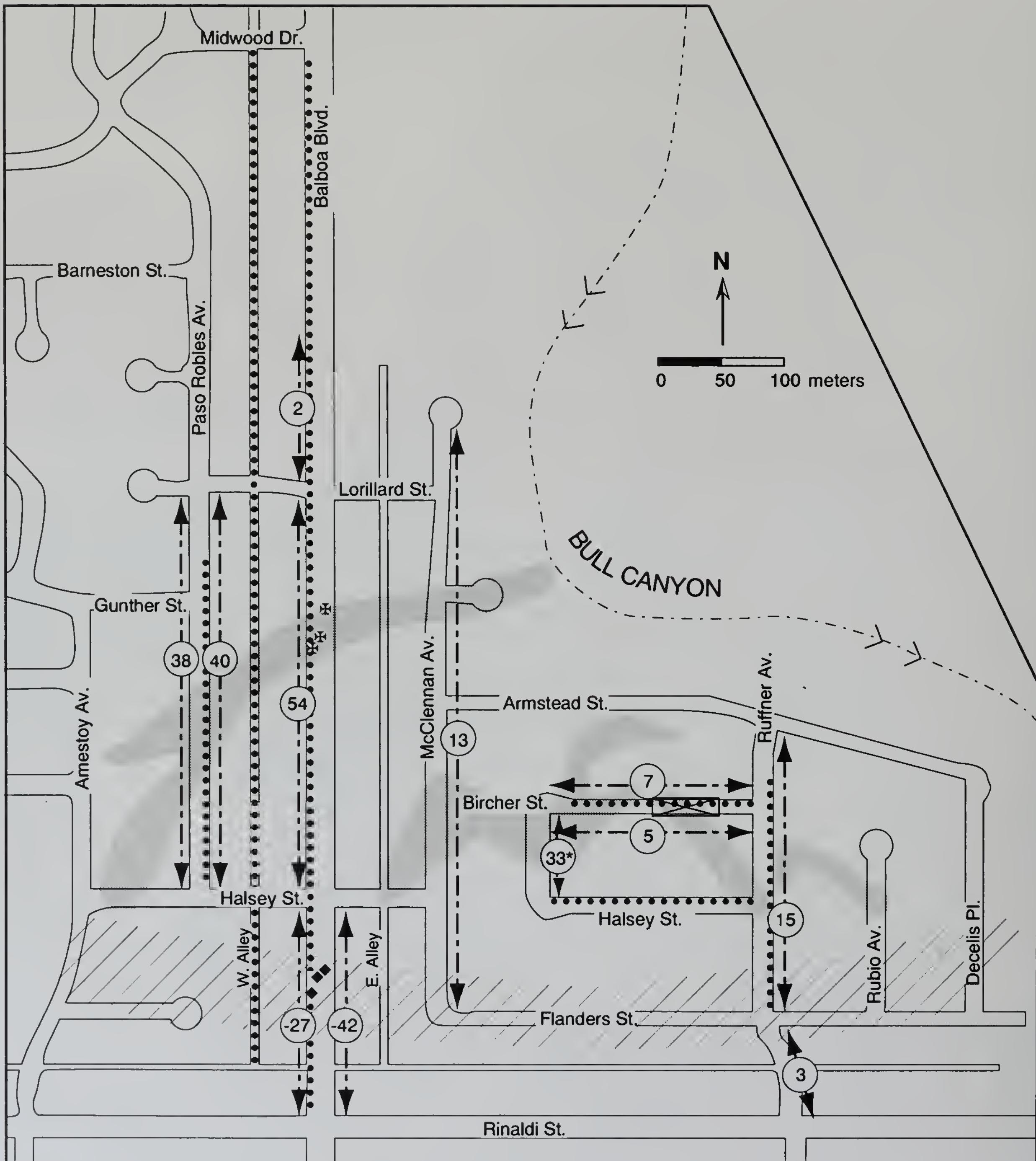
Photo 3. Spalled and thrust-shortened curb at northwest corner of Halsey St. and Ruffner Ave. This type of feature is common in the zone of compression near Flanders St. Photo by M.J. Rymer.

Survey Data

To quantify deformation across the broad, compound zone of cracks in the area west of Bull Canyon, we made detailed surveys of curbs, sidewalks, and concrete drainage gutters. These surveys consist of (1) measurements of longitudinal (length) changes in sidewalks from sums of discrete displacements, (2) measurements of lateral and vertical deformation of curbs and gutters from total-station surveys, and (3) measurements of possible afterslip from repeated total-station surveys of a monumented quadrilateral on Bircher St.

Although the significance of individual crack measurements in pavement may be suspect, because of the problems of decoupling discussed above, cumulative net displacement derived by summing individual measurements across the entire deformation zone should closely reflect the total amount of permanent ground deformation along the trend of the profile. Results of the longitudinal deformation surveys (Figure 4) show that a maximum measured N-S extension of 54 cm occurs at Balboa Blvd. across the principal subzone of tension cracks; farther east, 33 cm of N-S extension is measured where tension cracks cross the N-S road connecting Bircher and Halsey Sts. (Figure 4). Measurements from the east side of Balboa Blvd., between Halsey and Rinaldi Sts., yield a net N-S convergence of 42 cm across the east-trending subzone of compressional deformation described above. Only 27 cm of N-S convergence, however, is documented between the same streets along the west side of Balboa Blvd. (Figure 4). The large disparity in these two closely spaced measurements may reflect difficulties inherent in trying to quantify compressional deformation in concrete. As opposed to extensional deformation in the area, which is expressed almost exclusively as discrete, readily measured fractures, compression can be accommodated by crushing and spalling of material and by tilting and rotation of individual slabs. Some compression may also be absorbed by the concrete. Hence, measurements of net compression presented here are considered to be minimum estimates.

The amount of lateral and vertical deflection of roads in the area west of Bull Creek is determined from precisely surveyed, closely spaced (<10 m) curb or gutter locations along profiles that extend (where possible) completely across one or more zones of deformation. For each profile, the deflection is defined as the distance between surveyed curb locations and a linear regression line derived from the straight, undeformed portion of the



EXPLANATION

Zone of concentrated tension cracks

Zone of concentrated compressional features

Line of total station survey of laterally and vertically deflected curb edges (see figs. 8 and 10)

Tensile failure of water and gas pipelines

Compressive failure of water and gas pipelines

Net longitudinal deformation as measured by summing displacements in sidewalks. Arrows designate extent of survey line; numbers are net extension (positive) or net compression (negative) in cm.

Location of monumented quadrilateral for afterslip detection.

* net deformation shown is average of two repeated measurements taken 1/22/94 (33.9 cm) and 1/24/94 (32.6 cm)

Figure 4. Generalized map of the Granada Hills deformation zone west of Bull Canyon, showing locations of survey lines and amounts of longitudinal (street parallel) deformation.

profile. A basic assumption of this approach is that curbs were straight and had a constant slope prior to the earthquake.

Three N-S profiles located between Balboa Blvd. and Paso Robles Ave. show that curbs and drainage gutters are deflected eastward across the principal subzone of tension cracks (Figure 5). This deflection, which reaches a maximum of ~30 cm, appears as left-lateral deformation across the subzone (Photo 4) and is consistent with observed southeast-directed extension. A nearly equal amount of westward (or right lateral) deflection is observed on the profiles (of Balboa Blvd. and the alley west of it) where they cross the subzone of concentrated compressional deformation (Figure 5). This sense of lateral deformation is consistent with compression directed toward the southeast, which is the direction of ground movement observed in the extensional subzone to the north. Plots of vertical deflection along the Balboa Blvd. and west alley profiles (Figure 5) reveal that the ground-surface slope abruptly decreases ~0.3° across the subzone of tension cracks and steepens slightly within the subzone of compressional deformation. This deflection is most clearly observed in the alley, which appears to have been terraced and graded to a constant slope in the early 1960s.

Photo 4. View to the north across principal zone of tension cracks in the alley between Paso Robles Ave. and Balboa Blvd.. Eastward movement of the alley is clearly demonstrated by the apparent left-lateral deformation of the concrete drainage gutter where it crosses the crack zone. Photo by D.J. Ponti.

Measured profiles east of Balboa Blvd. (Figure 6) are consistent with field observations that suggest southeast-directed extension. Approximately 16 cm of eastward (left-lateral) deflection of Ruffner Ave. appears to be due to left-shear and extension on a southeast-trending subzone of cracks (Figure 4). East-trending Bircher St. is deflected sharply southward (left-laterally) where it crosses the same southeast-trending, left-extensional subzone that deforms Ruffner Ave., but appears to be deflected in the opposite sense (right-laterally) at its western end where it intersects an east-to-northeast-trending subzone of southeast-directed extension. Halsey St., one block to the south of Bircher St., shows similar left-lateral deformation within the southeast-trending subzone of cracks (near the intersection with Ruffner Ave.). Figure 7 illustrates how the sense of lateral deformation (either right or left) of roads in the area varies with respect to the trends of both roads and crack zones. Unlike the profiles west of Balboa Blvd., the elevation data for this area does not show any clear trends.

The longitudinal and lateral components of deformation presented above can be used to derive the magnitude and orientation of total horizontal displacement across the zones of tension cracks. As summarized in Table 1, computed horizontal displacements range from 22 cm to 60 cm, and displacement azimuths range from 133° to 164°. Vector azimuths shown in Table 1 closely parallel the local topographic gradient and are consistent with the range of displacement vector azimuths measured on individual cracks (130°-170°; Hecker and others, 1995).

Table 1. Total horizontal displacement across zones of tension cracks in the area west of Bull Creek, as derived from ground surveys.

Profile	Displacement (cm)	Vector Azimuth
Balboa Blvd., between Lorillard and Halsey St.	60	153°
Paso Robles Ave., between Lorillard and Halsey St.	43	158°
Bircher St., west of Ruffner Ave.	25	164°
Ruffner Ave., between Armstead and Flanders St.	22	133°

All of the observed displacement is inferred to have occurred as a result of the January 17 earthquake. Despite the claims of local residents that the cracks were "growing" during the days following the earthquake, repeated surveys of a monumented quadrilateral on

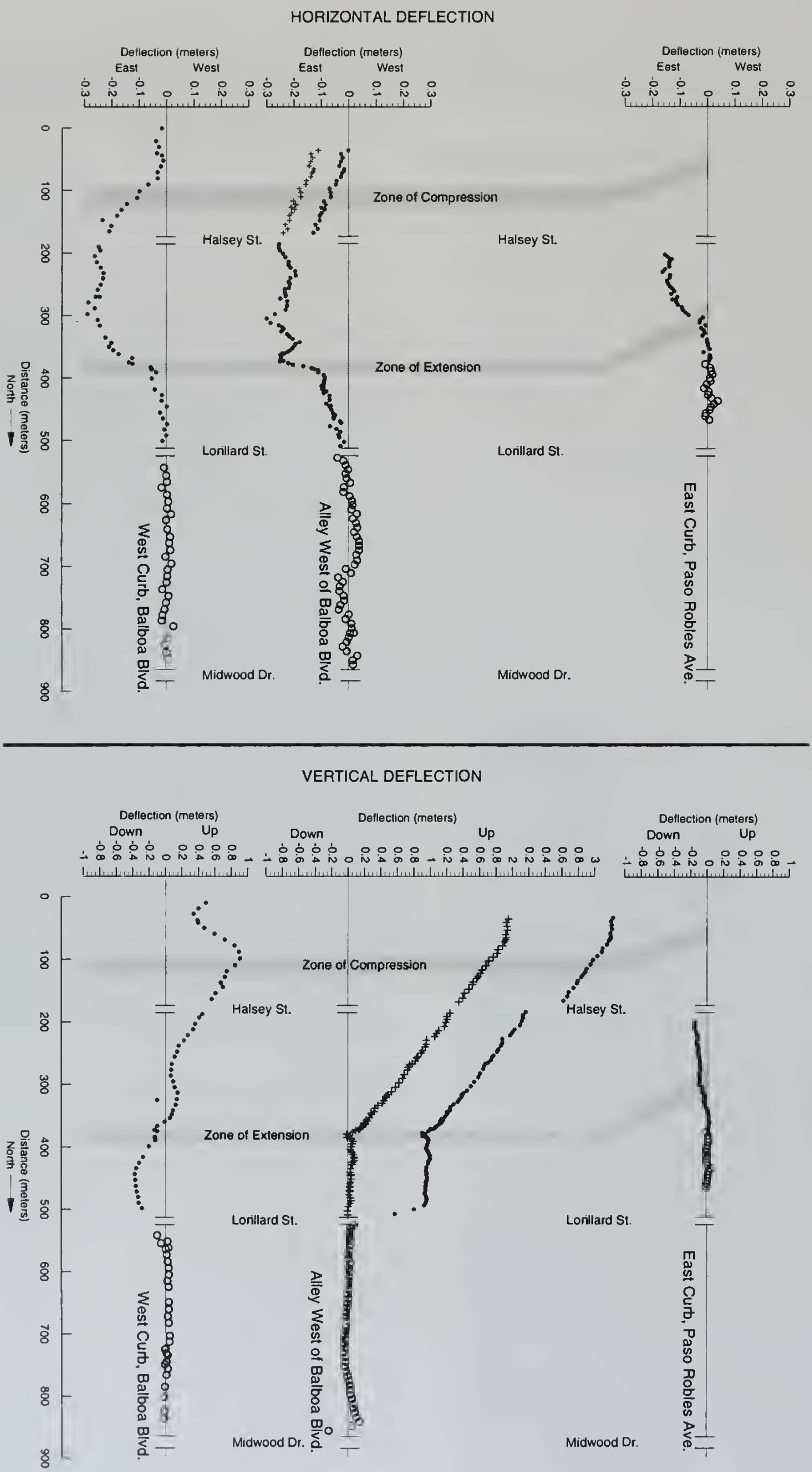


Figure 5. Plots of lateral and vertical deformation of concrete curbs and drainage gutters along N-S profiles between Balboa Blvd. and Paso Robles Ave. Locations of lines shown on Figure 4. Open circles designate stations outside of the deformation zone used to define straight line references; solid circles are stations presumed to be within the zone of deformation. Plus symbols are station locations corrected for man-made offsets across street intersections. Surveys show an abrupt eastward deflection of the profiles across the zone of extension and a nearly equal, although not nearly as abrupt, westward deflection with the zone of compression. Slopes also appear to decrease abruptly across the zone of extension.

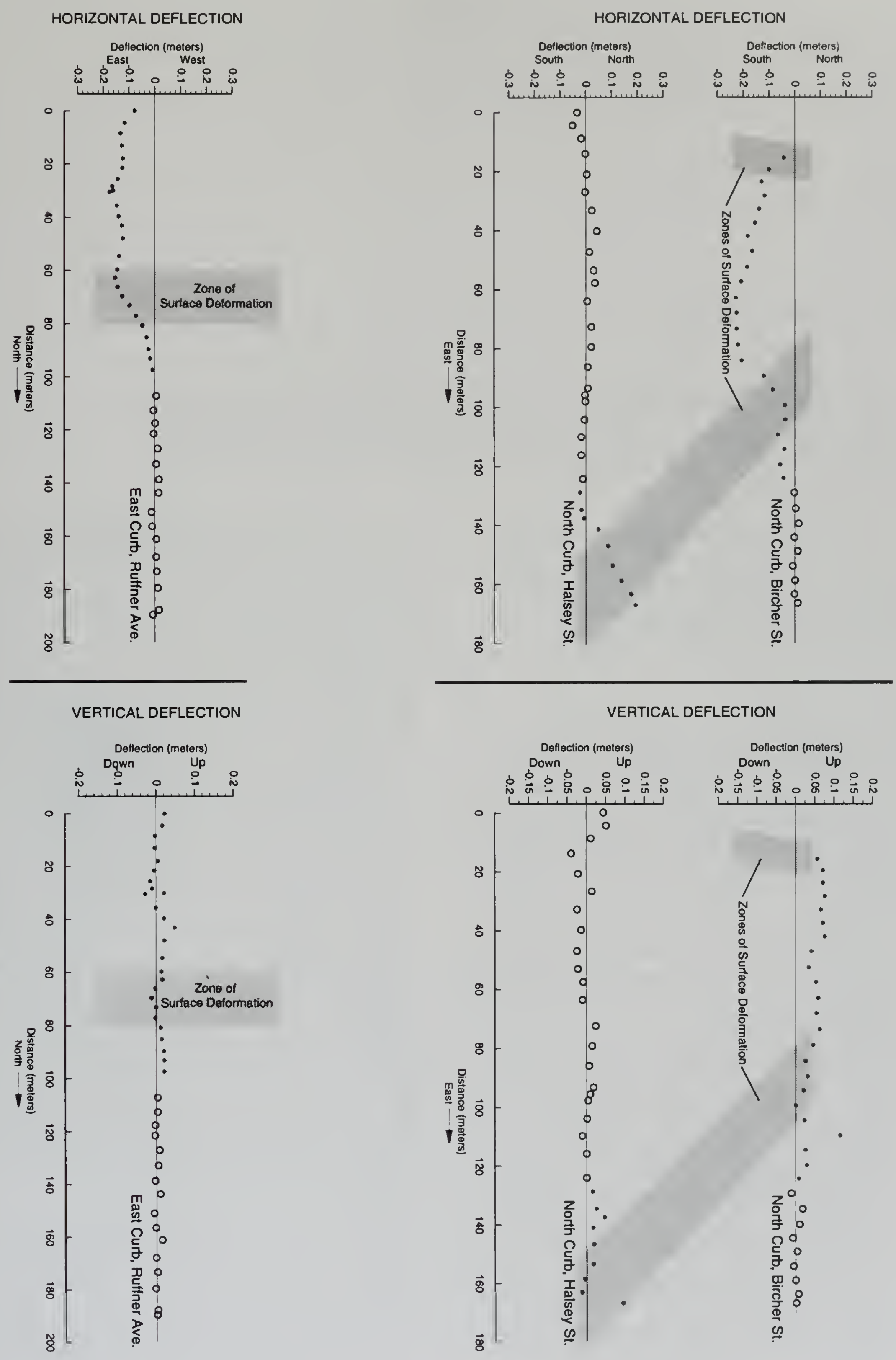


Figure 6. Plots of lateral and vertical deformation of concrete curbs along E-W and N-S profiles east of Balboa Blvd. Locations of lines shown on Figure 4. Open circles designate stations outside of the deformation zone used to define straight line references; solid circles are stations presumed to be within the zone of deformation. See text for discussion.

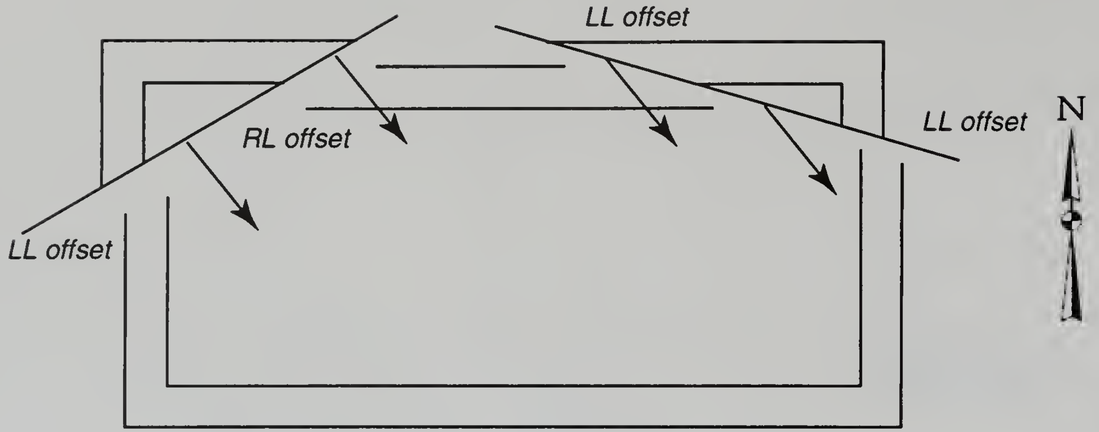


Figure 7. Diagram illustrating sense of lateral deflection of N-S and E-W roads across a region of SE extension, as is observed for the area west of Bull Canyon. Crack zones oriented NE-SW deflect N-S roads left-laterally (i.e., Balboa Blvd.) and E-W streets right-laterally (i.e., west end of Bircher St. near McClennan Ave.). Crack zones oriented NW-SE deflect N-S streets left-laterally (i.e., Ruffner Ave. near Halsey St.) and E-W streets left-laterally (i.e., Bircher St. near Ruffner Ave.).

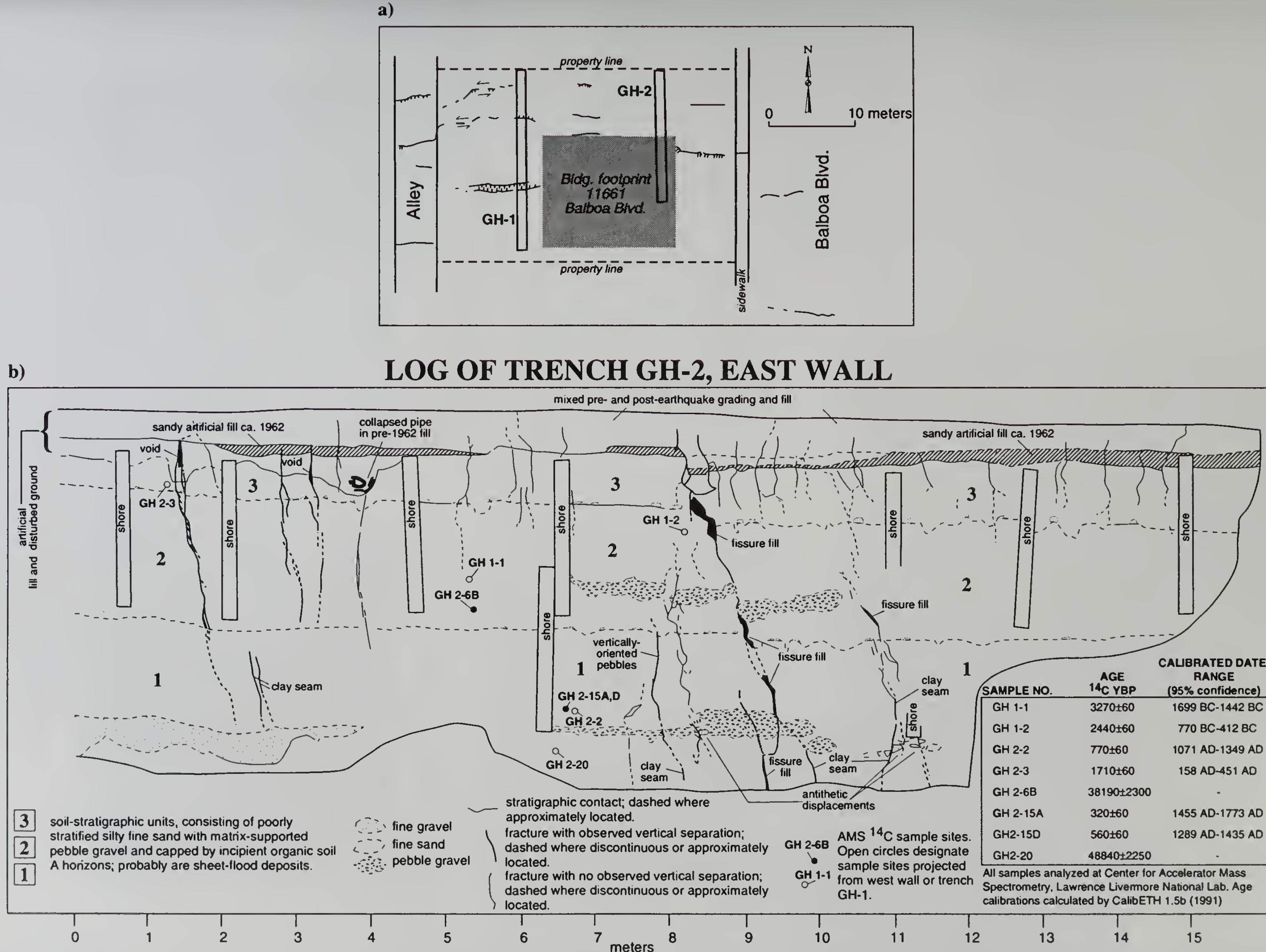
Bircher St. (see Figure 4 for location) show no evidence of ongoing deformation. A leveling survey along the alley west of Balboa Blvd., made during the weeks following the earthquake, also shows no evidence of afterslip (A. Sylvester, personal communication, 1994).

Trench Data

To evaluate the subsurface geometry of the mapped tension cracks and the possibility of prior ground deformation, we excavated two trenches across the principal subzone of extension west of Bull Creek. The trench site is a vacant lot on the west side of Balboa Blvd. that prior to the earthquake was occupied by a two-story single-family residence (11661 Balboa) constructed in 1962. The house was destroyed shortly after the earthquake by fire originating from the ruptured gas main on Balboa Blvd., although the house might already have been critically damaged by ground deformation. A number of prominent east-trending fractures cross the property (Photo 1 and Figure 8a). The largest fracture extends from near the site of the pipeline break westward into the front yard of 11661 Balboa, where at the time of our mapping it was partly obscured by the foundation and rubble of the destroyed house (Photo 2). This fracture does not clearly correlate with cracks farther west, although it may angle southwest beneath the foundation slab and connect with a small graben in the back yard (Figures 8a and Photo 5). We situated trenches GH-1 and GH-2 to expose the graben and the large front-yard fracture, respectively (Figure 8a), and made detailed logs of GH-2 (Figure 8b) and a portion of GH-1.

The trenches expose four principal stratigraphic units (Figure 8b). The youngest of these units is an undifferentiated artificial fill deposit that consists of layered and compacted sand and local surface soil, presumably placed in preparation for construction of the house, and relatively loose, reworked surface material that was laid down during post-earthquake grading of the lot. Below the artificial fill, unit 3 consists of a massive light brown silty sand with scattered fine gravel (Figure 8b). The unit is capped by a dark, clay-rich horizon, up to ~40 cm thick, that is probably the modern pre-development soil. This "plowed zone", which contains a concrete irrigation pipe and other man-made debris, appears to have been extensively modified by the agricultural activities that occurred here before the property was developed in 1962. The trenches also expose two older soil-stratigraphic units that are texturally similar to unit 3 and are capped by incipient, ~20-50-cm-thick organic soil A horizons. Interspersed in both units are discontinuous fine sand and silt beds and several gravel lenses containing subrounded pebbles and cobbles. The matrix of the lowermost unit (unit 1, Figure 8b) appears to coarsen gradually with depth. All of the units in the section are poorly stratified and extensively bioturbated, which makes accurate correlation of horizons across fractures difficult. The sediments probably represent sheet-flood and minor stream channel deposits originating from Bull Creek or its distributary channels.

The degree of soil development and the majority of AMS ^{14}C dates on charcoal obtained from the trenches point to a late Holocene age for the exposed sedimentary section. Specifics concerning the AMS dates are problematic, however (see Figure 8b for sample locations and dates). Three charcoal samples from within unit 1 give tree-ring-calibrated dates that range between 1071 and 1773 AD (95% confidence). Two of these dates are discordant, despite the fact that they were derived from



SAMPLE NO.	AGE ^{14}C YBP	CALIBRATED DATE RANGE (95% confidence)
GH 1-1	3270±60	1699 BC-1442 BC
GH 1-2	2440±60	770 BC-412 BC
GH 2-2	770±60	1071 AD-1349 AD
GH 2-3	1710±60	158 AD-451 AD
GH 2-6B	38190±2300	-
GH 2-15A	320±60	1455 AD-1773 AD
GH2-15D	560±60	1289 AD-1435 AD
GH2-20	48840±2250	-

Figure 8. (a) Map showing location of ground cracks at 11661 Balboa Blvd. and location of trenches GH-1 and GH-2. (b) Simplified log of east wall of trench GH-2. Movement on the principal crack in 1994 (located between meters 8 and 10) displaced base of the artificial fill 22 cm vertically, but displaced top of unit 1 only 12 cm.

Photo 5. View to the southeast of small graben on the west side of the lot at 11661 Balboa Blvd. (see Figure 8a). Photo by S. Hecker.

Although several fractures can be traced to the bottom of GH-2, only one (the large, front-yard fracture discussed above) has substantial vertical displacement. All of the displacement on this main fracture occurred in 1994, and the amount appears to decrease with depth in the trench. The base of the artificial fill steps down to the south 22 cm across the fracture, whereas the top of unit 1 has a vertical separation of only ~12 cm (Figure 8b). Because these stratigraphic boundaries are fairly planar and nearly horizontal, the difference in amount of separation across the fracture probably represents a true difference in vertical displacement. Two fractures in trench GH-2 have small, north-side-down displacements totaling ~4-7 cm. These displacements are present low in the section only, within but not at the top of unit 1 (Figure 8b), and may either represent minor antithetic adjustments in 1994 that failed to propagate higher in the section, or belong to a prior ground disturbance that dates from the time of unit 1 deposition. The clayey brown seams that characterize fractures near the base of the trench may be interpreted as additional evidence of an older fracturing event, or alternatively, as fracture-fills associated with the 1994 earthquake.

splits of the same sample. Furthermore, three samples from the stratigraphically higher units 2 and 3 yield older dates (from 1699 BC to 451 AD), and two other samples from GH-2 appear to be quite old (38,190 ± 2300 and 48,840 ± 2250 ^{14}C yr B.P.). These late Pleistocene dates are not consistent with either the degree of soil development or the other dates in the section. The scatter in the suite of dates makes it difficult to evaluate to what degree any of the dates accurately reflects the age of the section. However, if we assume that the older dates are from reworked material, it appears that the section is not more than 1000 years old, and may be closer to 600-700 years old.

The ground fractures extend across a zone more than 12 m wide in trench GH-2 (Figure 8b). They are expressed as combinations of open and closed cracks, narrow shear zones, clay seams, and water-laid (from pipe-burst flooding) fissure fills. Fractures are easiest to see in the artificial fill and in unit 3, where desiccation of clay-rich material causes cracks to open further. Fractures that appear to die out downward in unit 3 (Figure 8b) may be due to desiccation only and have no relation to ground failure. Fractures are generally more difficult to discern in unit 2 and in the upper part of unit 1, except where marked by pipe-and-fill sequences. Several fractures are well expressed as brown, clay-rich seams within the lowermost meter of unit 1. All of the fractures in the trench have steep dips, ranging from nearly vertical to ~70° S, although some dip steeply to the north over short intervals.

Lower Bull Canyon and Drainageways to the East

Another area of concentrated ground deformation in the Granada Hills–Mission Hills belt lies east of the area described above and follows the historical (pre-development) course of Bull Creek through the lower portion of Bull Canyon. Cracks are observed in asphalt, concrete, and bare ground along a reach of the drainage that had been modified through construction of a subsurface storm drain and, at the downstream end, filled for a housing development (Figures 3 and 9).

A 150-meter-long zone of cracks developed along the storm-drain alignment, on and at the base of the southwest wall of the present channel cut (Figure 3, locality 3). Individual cracks are as long as 50 m, have a decimeter or more of opening, and form vertical scarps that face toward the channel (Photo 6). Liquefaction may have contributed to ground failure here, as indicated by a small area of vented sand on the channel floor near the downstream end of the zone.

Photo 6. Tension crack on the southwest wall of the Bull Creek channel (view to the west; near locality 3, Figure 3). Photo by T. E. Fumal.

Upstream, to the north, a 100-meter-long zone of cracks formed in the middle of the channel floor (Figure 3, locality 4) along a pre-existing vegetation lineament that may mark the other side of the storm-drain excavation or some other artificial-fill boundary. A compressional welt and a tension crack with vertical separation down toward the center of the drain form the north and south halves, respectively, of this ground-failure zone. A 30-meter-long crack farther upstream high on the channel wall (Figure 3, locality 5) appears to be related to slope failure.

The 150-meter-long crack zone at locality 3 that follows the southwest wall of lower Bull Canyon is part of a longer zone of deformation that continues eastward onto Halsey St. and then southward onto Odessa Ave. (Figure 3). These streets follow the course of the old stream bed and are constructed on artificial fill placed in the channel (Figure 9). Top soil mounded against the sidewalk on the south and west sides, respectively, of Halsey St. and Odessa St. (Photo 7) and pavement compressed against concrete curbs on the other sides of these roads are evidence for compression orthogonal to both Halsey and Odessa. Tension cracks formed parallel to the compressional features, but are less extensive and record less movement (typically ~1-2 cm opening versus ~5 cm shortening). A series of closely spaced tension cracks also developed transverse to Odessa Ave. (Figure 3). Another zone of tension cracks takes a path through several houses and lots east of Odessa Ave. (Figure 3, locality 6). As shown in Figure 9, these cracks follow an abandoned meander bend along the old incised channel of Bull Creek.

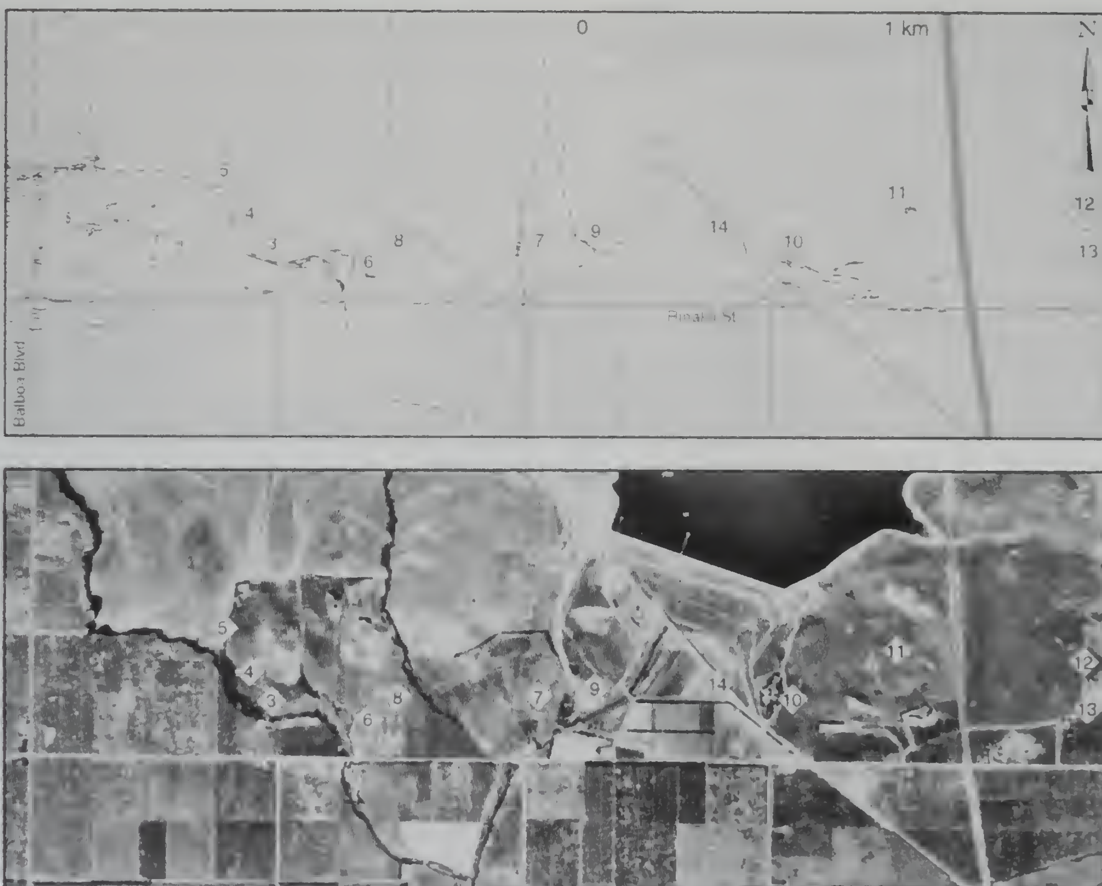


Figure 9. 1947 aerial photograph of the Granada Hills–Mission Hills area showing location of drainage channels prior to urbanization. Many of the ground cracks that formed in 1994 (shown in line drawing) are adjacent to or overlie these old channels (localities 3-9). Note particularly the geometry of the ground cracks at locality 6 and the existence of an abandoned meander bend at the same location.

Other roads built on artificially filled channels were also damaged during the earthquake. A set of transverse cracks formed on Woodley Ave., a road that replaced a small tributary drainage of Bull Creek (Figures 1 and 9, locality 7). In addition, a local concentration of road-parallel deformation developed along a northwest-trending segment of Halsey St., near where it joins with Gothic Ave. to mark the former course of another tributary stream (Figures 1 and 9, locality 8).

Photo 7. Top soil thrust over sidewalk along the west side of Odessa Ave. View to the south. Photo by D.P. Schwartz.

Ground cracks also developed across the campus of Kennedy High School, which is built above a buried, channelized portion of Bull Creek south of the main area of focus for this study (see Figure 1 for location). Ground deformation at the school may reflect permanent lateral movement of subsurface material toward the channel, as apparently occurred farther upstream along the open but channelized eastern branch of Bull Creek. At this location within the study area (Figure 1, locality 9), a zone of tension cracks developed in nearly level ground adjacent to the channel.

Mission Hills

Two subzones dominated by tension cracks and small normal-fault scarps developed low on the south flank of the Mission Hills anticline west of Interstate 405 (Photo 8). The subzones are each about 350 m long, approximately parallel, and cross from open ground into a densely developed housing complex (Figure 1, locality 10). The cracks follow the general contour of the moderately steep (~15% gradient) hillside and appear also to follow bedding planes in the upper Miocene Modelo Formation and the upper Miocene and lower Pliocene Towsley Formation, which dip in the downslope direction (~60-70° to the south; Dibblee and Ehrenspeck, 1991; Barrows and others, 1975a). The amount of horizontal extension measured on cracks in each subzone is generally less than 5 cm, although more than 10 cm of extension is observed along the middle portion of the upper subzone of cracks. A small side-hill bench, along which graben and other cracks formed during the earthquake, is present within the upper subzone and is evidence that ground movement had occurred here previously. Where the two subzones cross into the area of multi-family housing on the hillside, they are expressed as diversely oriented cracks in roads, driveways, walkways, and storm drains.

Three other areas of ground cracks formed on the Mission Hills anticline during the earthquake. One zone of tension cracks, approximately 100 m long and 60 m wide, developed adjacent to an apartment complex on a cut-and-fill slope in Quaternary alluvium high on the south-facing hillside west of I-405 (Figure 1, locality 11). This zone has an arcuate shape that is concave downslope, suggestive of a landslide crown. Another area of cracks occupies a similar setting east of I-405. Here, tension cracks on the hillside developed upslope from a compressional welt that formed locally on the inside edge of a large cut bench (Figure 1, localities 12 and 13). A third zone of cracks is aligned along the western base

Photo 8. Example of tension crack and small scarp on south flank of the Mission Hills anticline (near locality 10, Figure 1). View to the northwest. Photo by C.D. Garvin.

of the anticlinal hill, perpendicular to the axis of the Mission Hills anticline (Figure 1, locality 14). This line of cracks is about 150 m long and follows the upper end of a small, pre-existing landslide, which appears to have developed in colluvial deposits at the foot of the hillslope.

ORIGIN OF GROUND DEFORMATION

In the area west of Bull Canyon, the pattern of tension cracks and compressional deformation is suggestive of surficial mass movement. Pertinent features are (1) a somewhat arcuate crown scarp defined by the principal subzone of tension cracks that crosses Balboa Blvd.; (2) internal scarps developed in the vicinity of Bircher St.; (3) a poorly defined lateral margin in the vicinity of Ruffner Ave., and (4) a compressional toe expressed along Flanders St. (refer to Figure 3). A reduction in slope within the confines of the "slide" mass and an apparent mounding of material in the toe region, evidenced by some of the survey data (Figure 5), is suggestive of a component of back rotation within the mass. Furthermore, the direction of ground movement (to the southeast) closely parallels the local topographic gradient, and crack trends are strongly influenced by small-scale topographic variations. For example, the principal, northeast-trending subzone of cracks that crosses Balboa Blvd. abruptly turns southeast to run along the rim of the 7-9 m deep Bull Canyon incision instead of continuing across it (Figure 3). This line of evidence suggests that deformation is confined to within ~10 m of the ground surface.

Surveys of longitudinally and laterally deformed roads substantiate the occurrence of shallow, southeast-directed mass movement west of Bull Canyon. N-S roads shifted eastward and E-W roads shifted southward within areas encompassed by the ground cracks and compressional deformation (Figures 5 and 6). The lateral deflections observed across the zones of tension cracks appear to fully recover across the zone of compression. Similarly, amounts of extension on the tension cracks appear to be largely or entirely compensated by compression farther downslope. Although the longitudinal road surveys suggest that net extension occurred across the compound zone of deformation (Figure 4), the actual amount of compression is probably under-represented by the measurements. In fact, compression and extension as measured in water and gas pipelines beneath Balboa Blvd. are approximately equivalent (O'Rourke, 1994; O'Rourke and Palmer, 1994).

The apparent lack of significant net ground deformation beyond the ~500 m width of the crack zones argues for surficial mass movement and against tectonic surface faulting as the origin of deformation. Also, the shape of the deformation field as expressed in the lateral surveys (Figures 5 and 6) appears not to be consistent with the elastic deformation that would be produced by tectonic faulting (Thatcher, 1990). Even if the displacements were a result of elastic deformation, the narrow breadth of the deformation field would indicate a very shallow depth to the base of the fault.[1] The character of deformation seen in the trenches on Balboa Blvd. also argues against a faulting mechanism. Vertical displacement on the main fracture zone in trench GH-2 appears to decrease with depth (Figure 8b), a phenomenon that is not consistent with tectonic faulting, but may be explained by shaking-induced compaction within the loose, near-surface sediments.

Downslope mass movement appears to best account for the set of deformation characteristics observed west of Bull Canyon, but the reasons for ground failure here are unclear. The gradient is gentle (~2%), so the area does not appear especially susceptible to slope failure. Also, we are unaware of any subsurface horizons with low shear strength that could accommodate a slide plane. However, little is known about subsurface conditions in the area, beyond a general understanding that the piedmont is formed on predominantly fine-grained Holocene alluvium. Compaction of fine, loose sediment may have contributed to ground deformation, but this possibility has not been evaluated. Liquefaction may also have played a role in ground failure, but no evidence for liquefaction was observed at the surface, and no evidence exists for widespread shallow ground water. Recent borings drilled adjacent to Bull Canyon encountered water at a depth of ~9 m (F. Dennison, personal communication, 1994), but regionally, the ground water table may be >30 m beneath the surface (California State Water Rights Board, 1962). Regardless of the particular sedimentologic and hydrologic factors involved, ground motion is likely a necessary component of the mechanics of failure and downslope movement in this low-gradient area.

Zones of tension cracks on the south flank of the Mission Hills anticline accommodated downslope-directed movement on steep slopes, and all but perhaps the two most extensive zones are clearly expressions of shallow slope failure. Cracks in the two ~350-meter-long zones on the hillside west of the I-405 freeway,

---

[1] For elastic deformation, coseismic displacement is defined by the arctan function, $u = \frac{s}{\pi}\left(\tan^{-1}\left(\frac{d}{x}\right)\right)$, where u= coseismic displacement at distance x from the fault, s= coseismic displacement at the fault, and d= depth to the base of faulting. For a fault where s 0.3 m, u 0.01 m, and x 300 m, depth of faulting would only be ~31 m.

which conform to the attitude of bedding in the underlying bedrock, have displacements consistent with bedding-plane faulting and, thus, *may* have accommodated arching and extension during possible coseismic folding of the anticline. Alternatively, the bedding surfaces could have acted to control the geometry of slip planes within an incipient landslide complex. This is a postulated mechanism for ground cracks produced in the Santa Cruz Mountains by the 1989 Loma Prieta earthquake (Ponti and Wells, 1991).

There is little suggestion of tectonic surface faulting in the rest of the Granada Hills–Mission Hills belt of deformation. Cracks along Bull Creek and its tributaries are directly associated with natural or artificial channel fill and were evidently caused by liquefaction and/or shaking-induced compaction of the fill and possibly of young, fine-grained stream deposits. Cracks on or near channel walls probably involved slope failure as well. Small sand boils, evidence of liquefaction, formed on the floor of lower Bull Canyon at a location just upstream from Halsey St. and the filled portion of the channel. In the vicinity of Halsey St. and Odessa Ave., which were both constructed along the former course of Bull Creek, the ground cracks are likely an expression of lurching or differential compaction between the artificial fill or the underlying stream deposits and the adjacent piedmont alluvium. Shaking-induced lurching of material probably explains the combination of tension cracks that follow the old meander-bend channel margin east of Odessa Ave. and the compressional features observed within the road itself, above the old stream bed (Figure 9). However, moisture- or deposition-related differences in the response of the stream deposits to shaking may have also contributed to the pattern of deformation seen along the two roads. Cracks were also observed here locally following the 1971 San Fernando earthquake (Barrows and others, 1975b), a further indication that ground shaking may be an underlying cause of deformation in this area.

Shaking is a viable mechanism for the concentration of ground deformation in the Granada Hills–Mission Hills area, as large ground motions were experienced here during the main shock. Strong shaking was widespread throughout the northern San Fernando Valley, apparently because of the combined effects of radiation pattern and directivity (USGS and SCEC, 1994; Wald and Heaton, 1994), and long-period ground motions were especially high within the belt of deformation. The peak ground acceleration recorded by a strong motion instrument at the LADWP Rinaldi Receiving Station (Figure 1) is rather high (0.83 g), but the peak velocity here, which is more indicative of ground strains, is the highest recorded for any earthquake anywhere (170 cm/sec, Wald and Heaton, 1994). In addition, a large aftershock (M_L=5.9) occurred directly beneath the Mission Hills (Figure 1) only 62 seconds after the main shock and may have exacerbated strong shaking locally.

The characteristics of ground deformation across the Granada Hills–Mission Hills belt vary in detail, but cracks in all of the zones appear to reflect control by local topographic and near-surface geologic conditions. Although most of the deformation appears to be an expression of shallow ground failure, site-specific mechanisms of failure generally are not known. The origins of deformation probably vary between zones and may involve one or more of the following shallow-seated phenomena: slope failure, lurching of surficial deposits, compaction of loose sediment, and liquefaction. The shallow nature of most or all of the deformation indicates that the belt as a whole is not a direct expression of tectonic surface faulting or of tectonic deformation due to subsurface faulting and folding. Moreover, the above-postulated deformation phenomena largely require that ground motion was an integral part of the deformation process in the region.

RELATION OF GROUND DEFORMATION TO DAMAGE PATTERNS

Judging from effects of the 1989 Loma Prieta earthquake, damage from ground deformation in non-surface-faulting earthquakes is relatively inconsequential (Holzer, 1994). However, in the case of the Loma Prieta earthquake, the largest and greatest concentration of ground deformation occurred in rural areas (U.S. Geological Survey Staff, 1990). In contrast, the Northridge earthquake produced significant ground cracks in developed areas and therefore offers an excellent opportunity to assess the earthquake risk from secondary ground deformation in a suburban environment. Such an assessment is important for cost-effective mitigation.

Damage to well-constructed and maintained infrastructure (roads and utilities) in Granada Hills and Mission Hills appears largely due to earthquake-induced ground deformation. Damage occurs at most locations where zones of ground cracks cross infrastructure corridors. More importantly, earthquake damage is largely nonexistent in areas where ground cracks are absent. Exceptions are largely limited to pipeline failures attributable to corrosion or poor welds (T. O'Rourke, personal communication, 1994). Shaking-induced decoupling of roads and sidewalks generally enhances damage such that fracture zones are typically broader and more extensive in pavement than in adjacent bare ground (e.g., see Figure 3 along Balboa Blvd. and Paso Robles Ave.).

The relation between ground deformation and structural damage is more difficult to discern. Most structures in the Granada Hills–Mission Hills deformation belt are relatively modern (<30 years old), one or two story, single-family wood-frame houses. Many of the houses are built on slab foundations that are not steel-reinforced. Despite the high ground accelerations, buildings of similar vintage and construction within the greater San Fernando Valley performed quite well, typically sustaining only cosmetic damage. In the Granada Hills–Mission Hills area, however, many structures appear to have sustained significant structural damage.

To assess the spatial relation between structural damage and permanent ground deformation in the area west of Bull Canyon, we've compared the locations of houses determined to be safety concerns as of March 17, 1994 (inspection-tagged either "red", which bars entry, or "yellow", which limits entry) with the locations of cracks (Figure 3). As shown on Figure 3, tagged buildings commonly lie over or adjacent to mapped cracks, and the general pattern of damage largely reflects the pattern of deformation. The correlation between damage and deformation is especially evident along the northeast-trending subzone of tension cracks between Bull Creek and Paso Robles Ave. and within the subzone of compression along Flanders St.. Many structures within the crack zones suffered cracks and displacements within their foundations as well (Photo 9). Based on these observations, we suggest that structural damage in the area is largely the result of the permanent ground deformation that accompanied formation of the ground cracks. This evaluation is preliminary, because the damage information we received in March of 1994 is not complete. Factors other than ground deformation, such as building design and construction practices, may account for a sizable proportion of damage, and we are gathering additional information on the full scope of damage in the area. Clearly, however, ground deformation contributed significantly to the structural damage observed in the Granada Hills–Mission Hills area.

Photo 9. Foundation slab of a house broken by a ground crack (arrow), south side of Armstead St. The house was one of two on the street that were substantially damaged and assigned "red" inspection tags (Figure 3). Photo by M.J. Rymer.

DISCUSSION AND CONCLUSIONS

The character and pattern of ground deformation in the Granada Hills–Mission Hills area lead us to conclude that the primary mechanism for the deformation is shallow ground failure induced by strong shaking. However, this explanation alone does not address the question of why the deformation is localized along the Mission Hills Fault Zone and anticline. The spatial relation of the deep geologic structure with the surficial ground failures suggests that there may be an indirect linkage between the two.

We suggest three possible ways in which development of the belt of ground cracks may be related to the presence of the underlying fault and fold. These are (1) the Mission Hills Fault served to focus seismic energy, resulting in locally greater levels of shaking that triggered ground failures along the surface projection of the fault; (2) displacement occurred on the Mission Hills fault, releasing seismic energy that would have served to enhance ground motions locally; and (3) displacement within the Mission Hills Fault Zone and accompanying folding produced broad scale deformation of the ground surface that, in conjunction with shaking, served to trigger shallow ground failure. As previously discussed, long-period ground shaking was especially strong within at least a portion of the deformation belt. The phenomenon of fault zones acting as seismic wave guides has apparently been observed for the Landers earthquake (Li, and others, 1994), so there may be some basis for presuming that the Mission Hills Fault could act to enhance shaking locally. At present, analyses of the earthquake source (USGS and SCEC, 1994; Wald and Heaton, 1994) are not detailed enough to address whether slip occurred on the Mission Hills Fault during the earthquake. This issue may be resolvable with forthcoming analyses of more complete sets of seismic and geodetic data.

The possible role of the Mission Hills Fault in producing the belt of ground cracks in the Granada Hills–Mission Hills area raises the intriguing possibility that the ground failure here may be unique to Northridge-type earthquakes. If true, the displacement history of fractures in the zone could yield a direct estimate of the recurrence interval for the fault that produced the Northridge earthquake. Evidence for recurring displacement in the belt includes the side-hill benches that coincide with 1994 fractures in the Mission Hills and the possibility of an older late Holocene event exposed deep in trench GH-2 on Balboa Blvd. The stratigraphic level of the possible prior event in GH-2 suggests that earthquakes capable of producing the requisite ground motions (Northridge-type events?) may be relatively rare. On the north side of the Santa Susana Mountains in Potrero Canyon, where shaking-related ground deformation also occurred in 1994, paleoseismic data similarly indicate a relatively long time interval (~1000 years) between displacement events (Rymer and others, 1995, this volume).

The results of this study suggest that areas near the up-dip projection of a concealed fault zone that are underlain by young, unconsolidated sediment or steeply dipping bedrock may be susceptible to ground failure during an earthquake. Nonetheless, the risk associated with this type of ground-surface deformation may be small if, as preliminary evidence from this study indicates, time intervals between deformation events are long (on the order of 1000 years). More work is needed, however, both to better address the recurrence history of the Granada Hills–Mission Hills deformation belt and to evaluate the regional extent of the hazard, before risk can be assessed confidently.

Specific zones susceptible to failure will be difficult to identify, however, if they are as discontinuous and geomorphically subtle as those in the Granada Hills–Mission Hills area. Even with the benefit of hindsight, it is difficult to recognize features within the belt of 1994 deformation that would have foretold where failures were to occur. Although the sidehill benches on the south flank of the Mission Hills anticline could have been identified prior to the Northridge earthquake, such features may not have been readily attributed to earthquake-induced deformation. The lack of clear surface evidence of prior deformation in the area west of Bull Canyon makes it unlikely that a potential for ground failure would have been recognized there before the earthquake. In addition, because of the surficial, non-tectonic nature of ground deformation in the belt, the locations of older failures might not be precise predictors of where future failures will develop.

Although difficulties such as those discussed above would hinder mapping of discrete ground-failure zones, our understanding of the geologic conditions conducive to ground failure could be the basis for effective mapping of ground-failure susceptibility zones. Depending on the magnitude of the risk, hazard-mitigation practices within susceptibility zones (such as enhanced engineering of fills and reinforcement of building foundations to withstand small-displacement ground movements) could prove to significantly reduce the economic losses from secondary ground deformation in future earthquakes.

ACKNOWLEDGMENTS

We would like to thank Ms. C. DeRose and Mr. P. Glowaski of Knollwood Realty, and Mr. and Mrs. J. Denoff for arranging and providing access to the trench site on Balboa Blvd. We appreciate the insights shared by D. Schwartz, T. Fumal, and J. Treiman while the trenches were being logged. R.V. Sharp contributed notes from his longitudinal surveys in the area west of Bull Canyon. D. Schwartz and T. Holzer provided critical review of an earlier version of this manuscript.

REFERENCES

Barrows, A. G., Kahle, J.E., Morton, D.M., Saul, R.B., and Weber, F.H., Jr., 1975a, Geologic map of the San Fernando earthquake area, *in* Oakeshott, G.B., ed., San Fernando, California, earthquake of 9 February, 1971: California Division of Mines and Geology Bulletin 196, plate 2, scale 1:18000.

Barrows, A.G., Kahle, J.E., Weber, F.H., Jr., Saul, R.B., and Morton, D.M., 1975b, Surface effects map of the San Fernando earthquake area, *in* Oakeshott, G.B., ed., San Fernando, California, earthquake of 9 February, 1971: California Division of Mines and Geology Bulletin 196, plate 3, scale 1:24000.

California State Water Rights Board, 1962, Report of Referee, City of San Fernando, California Superior Court, County of Los Angeles: California State Water Rights Board, report 650079, v. 1, 258 p.

Dibblee, T.W., and Ehrenspeck, H.E., 1991, Geologic map of the San Fernando and Van Nuys (north 1/2) quadrangles, Los Angeles County, California: Dibblee Geological Foundation, scale 1:24000.

Dibblee, T.W., and Ehrenspeck, H.E., 1992, Geologic map of the Oat Mountain and Canoga Park (north 1/2) quadrangles, Los Angeles County, California: Dibblee Geological Foundation, scale 1:24000.

Goltz, J.D., ed., 1994, The Northridge, California earthquake of January 17, 1994: General Reconnaissance Report: National Center for Earthquake Engineering Research, Technical Report NCEER-94-0005, 130 p.

Hecker, S., Ponti, D.J., Garvin, C.D., Sharp, R.V., Hamilton, J.C., Powers, T.J., Fumal, T.E., Rymer, M.J., Prentice, C.S., Cinti, F.R., and Schwartz, D.P.,1995, Ground deformation in Granada Hills and Mission Hills resulting from the January 17, 1994 Northridge earthquake: U.S. Geological Survey Open-File Report 95-62, 11 p., 2 plates, scale 1:5000 and 1:2000.

Holzer, T.L., 1994, Loma Prieta damage largely attributed to enhanced ground shaking: EOS, Transactions of the American Geophysical Union, v. 75, p. 299-301.

Johnson, A.M., and Fleming, R.W., 1993, Formation of left-lateral fractures within the Summit Ridge shear zone, 1989 Loma Prieta, California earthquake: Journal of Geophysical Research, v. 98, p. 21,823-21,837.

Li, Y.G., Aki, K., Vidale, J., Lee, W.H.K., and Marone, C.J., 1994, Fine subsurface structure of the Landers Fault Zone; segmentation and rupture process inferred from fault zone guided waves: EOS, Transactions of the American Geophysical Union, v. 75, p. 343.

O'Rourke, T.D., 1994, Water system damage during the Northridge earthquake: NCEER Bulletin, v. 8, p. 6-8.

O'Rourke, T.D., and Palmer, M.C., 1994, Earthquake performance of gas transmission pipelines during the Northridge earthquake: NCEER Bulletin, v. 8, p. 1-5.

Ponti, D.J., and Wells, R.E., 1991, Off-fault ground ruptures in the Santa Cruz Mountains, California: ridge-top spreading versus tectonic extension during the 1989 Loma Prieta earthquake: Bulletin of the Seismological Society of America, v. 81, p. 1480-1510.

Rymer, M.J., Fumal, T.E., Schwartz, D.P., Powers, T.J., and Cinti, F.R., 1995, Distribution and recurrence of fractures in Potrero Canyon associated with the 1994 Northridge, California earthquake: California Department of Conservation, Division of Mines and Geology, Special Publication 116, p. 135.

Thatcher, W., 1990, Present day crustal movements and the mechanics of cyclic deformation *in* Wallace, R.E., ed., The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, p. 189-205.

Shields, K. E., 1977, Structure of the northwestern margin of the San Fernando Valley, Los Angeles County, California: Ohio University, M. S. Thesis, 82 p.

U.S. Geological Survey Staff, 1989, Preliminary map of fractures formed in the Summit Road - Skyland Ridge area during the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Open-File Report 89-686, scale 1:12000.

U.S. Geological Survey Staff, 1990, The Loma Prieta, California earthquake – an anticipated event: Science, v. 247, p. 286-293.

USGS and SCEC, 1994, The magnitude 6.7 Northridge, California, earthquake of 17 January 1994: Science, v. 266, p. 389-397.

Wald, D. J., and Heaton, T. H.,1994, A dislocation model of the 1994 Northridge, California, earthquake determined from strong ground motions: U.S. Geological Survey Open-File Report 94-278, 54 p.

Rymer, M.J., Fumal, T.E., Schwartz, D.P., Powers, T.J., and Cinti, F.R., 1995, Distribution and recurrence of surface fractures in Potrero Canyon asociated with the 1994 Northridge, California, earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 133-146.

DISTRIBUTION AND RECURRENCE OF SURFACE FRACTURES IN POTRERO CANYON ASSOCIATED WITH THE 1994 NORTHRIDGE, CALIFORNIA, EARTHQUAKE

by

Michael J. Rymer[1], Thomas E. Fumal[1], David P. Schwartz[1], Thomas J. Powers[1], and Francesca R. Cinti[2]

ABSTRACT

Widespread surface fractures formed around the margins of Potrero Canyon in association with the 17 January 1994 Northridge earthquake. These fractures are evidence of strong ground motions and the damage potential of a moderately large earthquake, especially in areas that are up dip from the hypocenter. The earthquake-induced effects in Potrero Canyon include surface fractures, liquefaction, and landslides. Vertical displacements across fracture zones vary from a few centimeters to greater than 61 cm. Surface fractures likely formed by alluvial compaction during strong earthquake shaking. Development of fractures near the alluvium-bedrock contact on both sides of the canyon that dip toward the canyon center and a net down-canyon motion of alluvial fill are evidence of a non-fault origin of the fractures. Trench investigations across several surface fractures showed steeply dipping breaks in a broad zone and, most importantly, evidence of two previous late Holocene episodes of surface fracturing. Timing of the penultimate event based on ^{14}C dates on detrital charcoal is about 880–1280 A.D.; an earlier event has an as yet undetermined Holocene age.

INTRODUCTION

The M 6.7 Northridge earthquake of 1994 strongly shook the Los Angeles urban region, and resulted directly in 33 deaths, over 20,000 people forced out of their homes, and an estimated $13–20 billion in damage (Hall, 1994). The earthquake was caused by slip on a previously unrecognized blind-thrust fault that dips south beneath the San Fernando Valley. Seismic slip on the fault propagated from a depth of about 19 km to about 8 km below the ground surface (USGS and SCEC, 1994). The search for surface faulting and surface fracturing was initiated within hours of the earthquake. Surface fractures formed in four areas: Potrero Canyon, the McBean Parkway area (Treiman, this volume), the Granada Hills-Mission Hills area (Hecker and others, this volume), and the Northridge-Reseda area (Figure 1).

This report describes surface and subsurface investigations of fractures that formed in Potrero Canyon, a 5-km-long, east-west-trending canyon developed in Pliocene rocks of the Pico Formation (Winterer and Durham, 1962), situated about 11 km west of Newhall and 22 km north-northwest of the 17 January main shock (Figure 1). Potrero Canyon lies up dip from the causative fault. Reconnaissance shortly after the earthquake found compressional surface deformation along the south side of the canyon suggestive of possible coseismic rupture. Aerial photographs of the Potrero Canyon area were taken by I.K. Curtis, on 21 January, at scales of about 1:2,000 and 1:6,000. These aerial photographs along with ground-based observations were used to map the surface fractures.

---

[1]U. S. Geological Survey, Menlo Park, California
[2]Istituto National di Geofisica, Roma, Italy

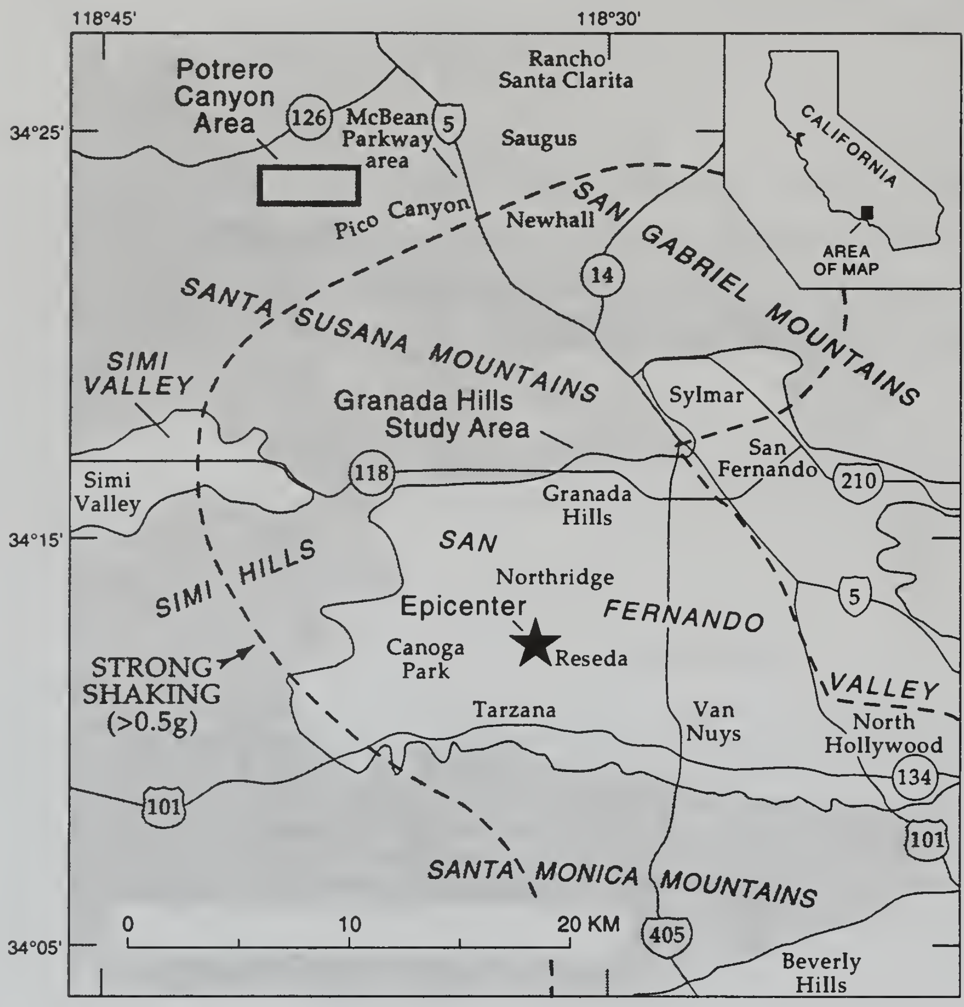


Figure 1. San Fernando Valley, California area, showing location of the Potrero Canyon study area relative to the epicenter of the 17 January 1994 Northridge earthquake (solid star). Dashed line, boundary of strong ground motion greater than 0.5 g.

SURFACE FRACTURES IN POTRERO CANYON

Extensive sets of surface fractures, with east-west and north-south limits of about 3.6 km and 1.3 km, respectively, formed in alluvium around the margins of Potrero Canyon (Figure 2; see also Rymer and others, in press, for larger-scale and more detailed plots of fractures). Most fractures occur along the contact between bedrock and alluvium, commonly near the base of hillslopes.

Characteristics of surface fractures vary between the south and north margins of the canyon. Deformation along the south side of the canyon commonly occurs as discontinuous narrow zones. Slip on fractures is dominantly extensional with a small lateral component. Compressional features formed only on the south side of the canyon, including the south side of a secondary canyon that extends to the southeast of the main canyon (Figure 2). This deformation appears as minor thrusts and low, broad mole tracks flanked by arcuate fractures. On the north side of Potrero Canyon, fractures formed wider discontinuous sets of cracks with similar dominantly extensional

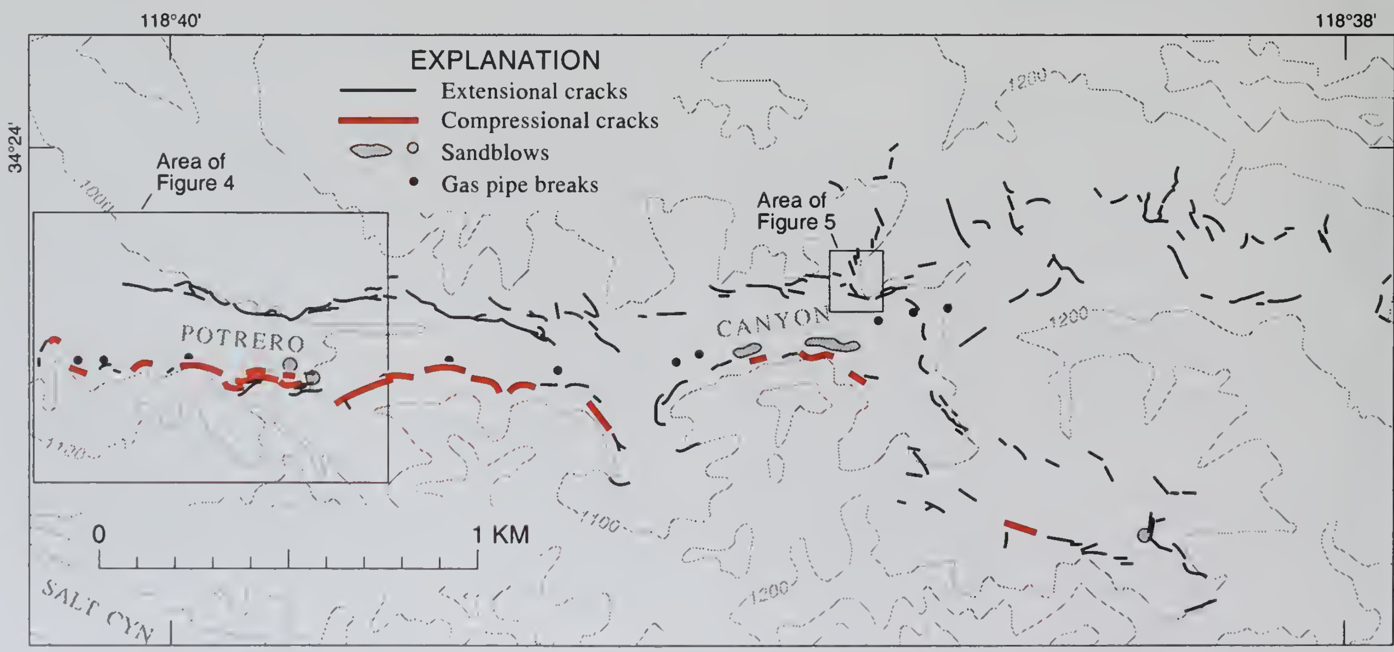


Figure 2. Surface fractures and other earthquake-induced features formed in Potrero Canyon in association with the 1994 Northridge earthquake.

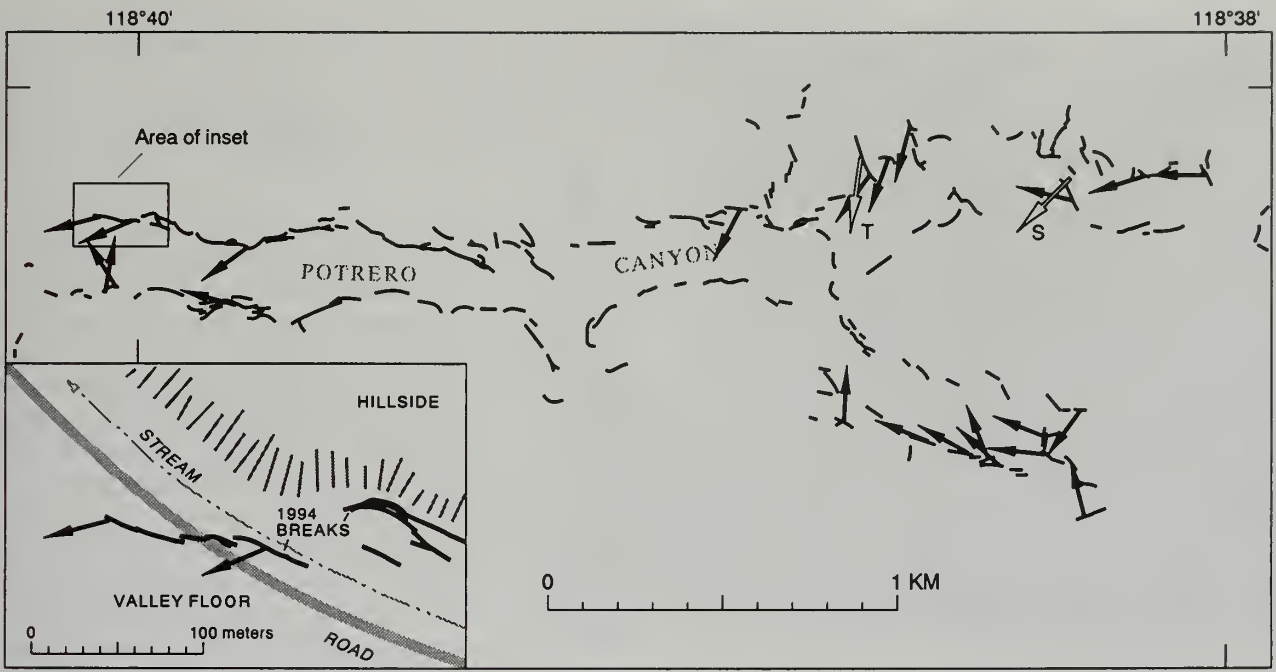


Figure 3. Map of horizontal slip directions across matching soil-block irregularities plotted relative to surface fractures in Potrero Canyon. Two hollow arrows in the northeast indicate horizontal slip directions of man-made features on the ground surface; these are marked with S = tank of soda ash and T = transformer. Inset map shows northwestern end of Potrero Canyon and 1994 surface fractures (heavy lines); horizontal slip directions show motion down canyon and not necessarily toward topographic free-face of the stream channel.

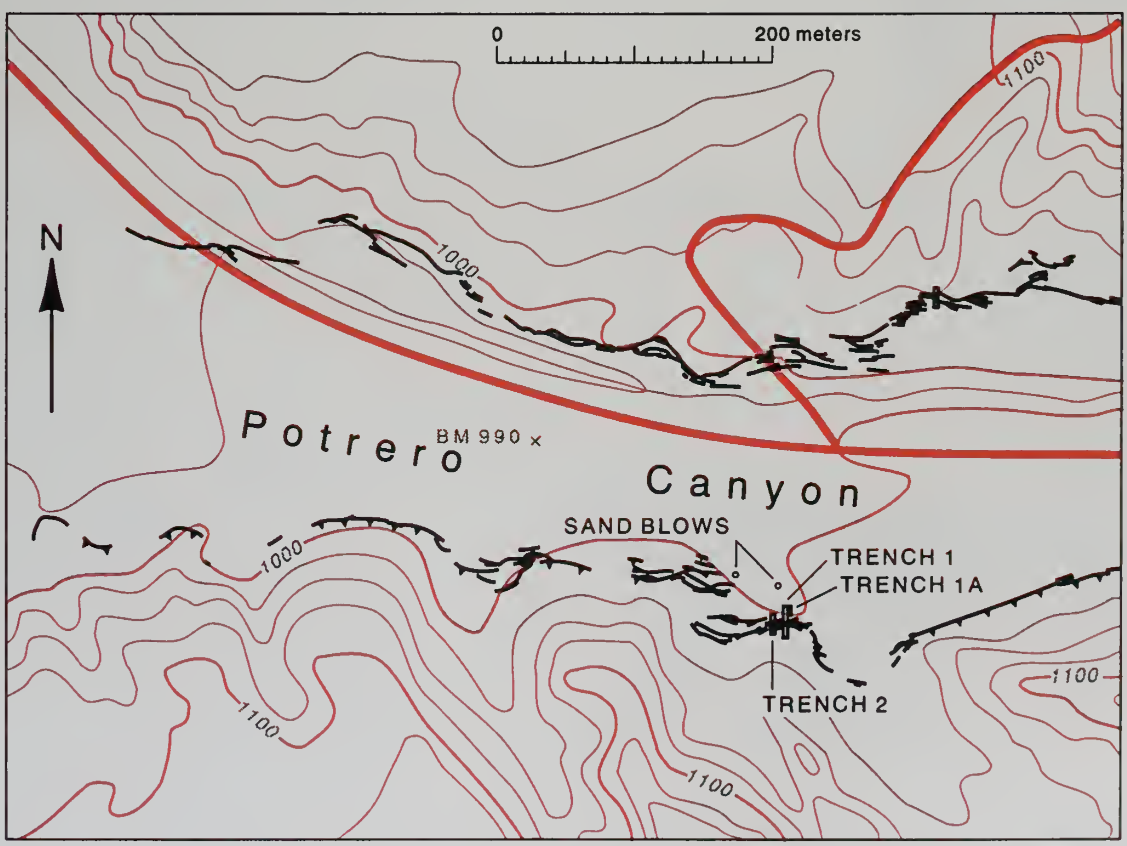


Figure 4. Western end of Potrero Canyon showing 1994 surface fractures and location of paleoseismic excavations described in text. Heavy lines, 1994 surface fractures; compressional fractures shown with teeth on upper plate.

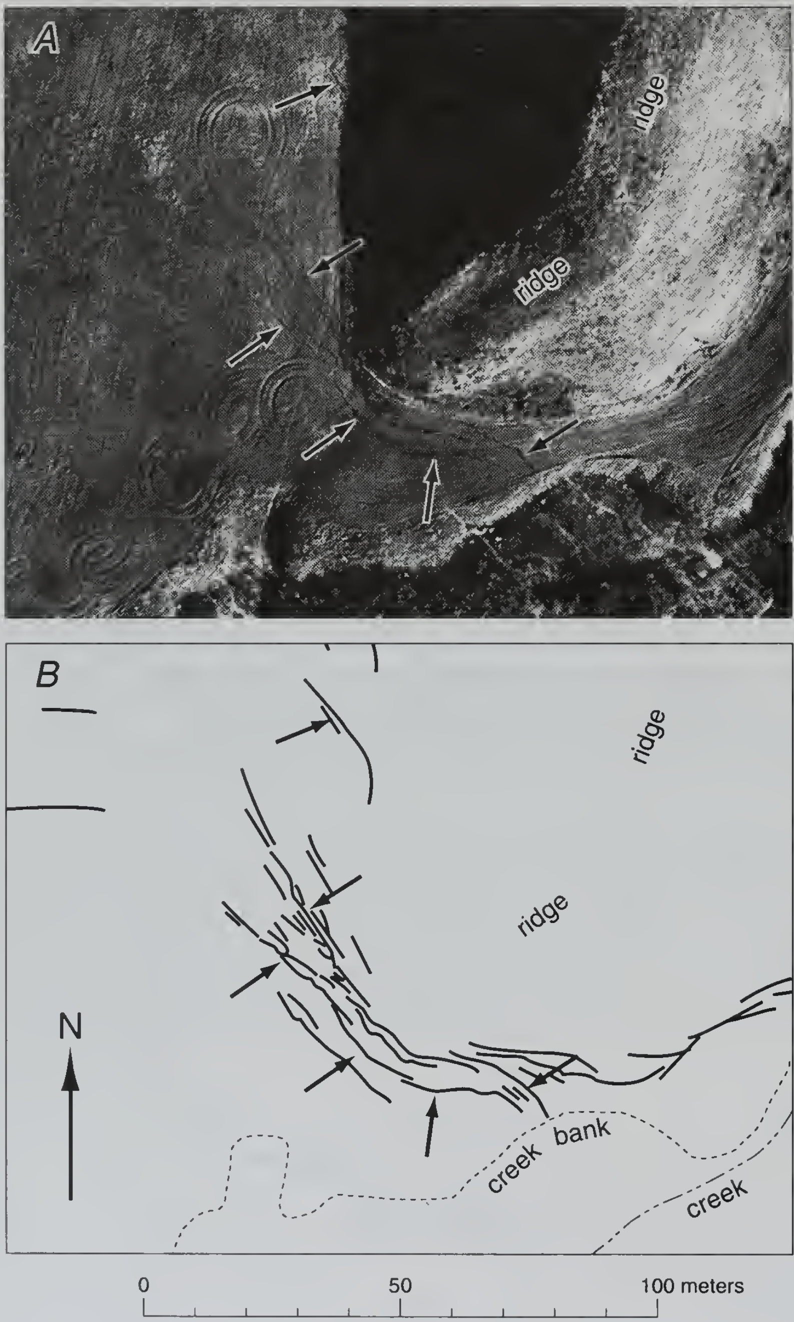


Figure 5. Surface fractures on north side of Potrero Canyon showing better developed cracks on west side of ridge spur that protrudes into canyon. *A*, aerial photograph of surface fractures, prominent fractures marked by arrow. Features seen on cultivated ground include plow marks, tractor turn marks (not crop circles), and cattle trails. *B*, Line drawing of same area shown in *A*. Heavy line, surface fracture.

displacements and small lateral components. Fracture zones on the north side of the canyon had widths as great as 30 m, whereas, the broadest zone of fractures on the south was only as wide as 10 m.

Slip components could only be measured locally and did not entirely span the crack sets. Grazing cattle were a primary cause of rapid degradation of the fractures. Also, rigid manmade features (for example, paved roads, curbs, walls) that best record displacement are not present in Potrero Canyon. Because of too few piercing points we show only the horizontal slip directions as measured across matching soil-block irregularities (Figure 3). Our measurements do not record the total displacement associated with this surface deformation. The closest approximation of total slip across the zone of cracks is a measurement at a site on the north side of the canyon about 400 m east of the western end of fractures. At this location measurement of the vertical component across three of the larger cracks in a 10-m-wide zone showed greater than 61 cm of slip. Estimates of maximum values of slip in Potrero Canyon for the vertical, compressional, and extensional components of slip across crack sets are about: 1 m, 0.2 m, and 0.3 m, respectively. After repeated total-station measurements we detected no evidence of afterslip or continued settlement across fractures (Rymer and others, 1995).

Several lines of evidence from both sides of the canyon indicate that alluvium moved toward the center and the down-stream end of the canyon. This is indicated in Figure 3, which shows horizontal slip direction measured across individual cracks or narrow crack sets. Also, extensional fractures on both sides of Potrero Canyon and in the side canyon most commonly occur or are more pronounced on the west sides of spurs or ridges that protrude into the canyons (Figures 2, 3, 4, and 5). An example of this phenomenon is found at the western end of fractures on the north side of the canyon. Here, cracks extend across a creek, and show horizontal slip directions toward the canyon center (Figure 3, inset). The cracks developed along the alluvium-bedrock contact, which is locally crossed by the creek, and slip along the cracks occurred in a general westward, down-canyon direction and toward the center of alluvial fill. Fractures on the south side are typically right-stepping and those on the north side are typically left-stepping, also indicating a net down-canyon (westward) movement of the alluvial fill.

Landslides and Related Ground Failures

The 17 January earthquake triggered thousands of landslides throughout the greater Los Angeles region (Jibson and Harp, 1994), including numerous slides that formed in the Potrero Canyon area. Although Jibson and Harp (1994) show only a few landslides in Potrero Canyon, their mapping was from small-scale aerial photographs that show only the larger slides. Dozens of small landslides in the hills surrounding Potrero Canyon were readily apparent in the field and on the 1:2,000-scale aerial photographs (landslides are not shown in Figure 2). The most common landslide types in the Potrero Canyon area are, in decreasing order of abundance, soil falls, soil slides, rock falls, and soil slumps. Landslides were most common in road cuts and along the margins of artificial fill deposits. The volume of individual landslides in the Potrero Canyon area varied, but was commonly small, less than 10 cubic meters. However, landslides on the north side of the canyon were quite extensive, locally extending from the ridge crest to near the bedrock-alluvium contact.

Extensional cracks along ridge crests, not associated with landslides, were also produced in the Potrero Canyon area by the Northridge earthquake. Locally, zones of cracking with overturned soil blocks suggest focusing of seismic energy. We saw these features on the ridge crest south of Potrero Canyon, but a systematic survey was not made of their distribution.

Sandblows are seen at several places in the valley floor of Potrero Canyon (Figure 2). They commonly formed near the south edge of the canyon, away from the principle stream channel and subsidiary drainages. The sand blows form cones, about 1–3 m in diameter, which locally coalesce in zones tens of meters long.

Pipe Breaks

Other earthquake-induced features in Potrero Canyon include pipe breaks in an east-west-trending natural gas line. Ten pipe breaks formed as tensile failures at pipe welds (T.D. O'Rourke, Cornell University, oral communication, 1994). The breaks were not co-located with surface fractures (Figure 2); pipe breaks were probably due to strong shaking, liquefaction, or differential down-canyon motion of alluvial fill rather than to movement across fractures.

TRENCHING INVESTIGATIONS

Eight trenches were excavated across the 1994 surface breaks to study the relation between the surface ruptures and bedrock structure and to observe whether there was a history of prior displacement. At most locations trenches expose only massive colluvium overlying bedrock. The most important observations are from two trenches located on the south side of Potrero Canyon, near its west end (Figures 4 and 6). Here, the variety of sedimentary deposits allows more detailed resolution of the depositional and structural history. The two trenches expose poorly to moderately well-lithified, steeply north-dipping mudstone, sandstone, and pebble conglomerate of the Pico Formation. The variety of rock types exposed

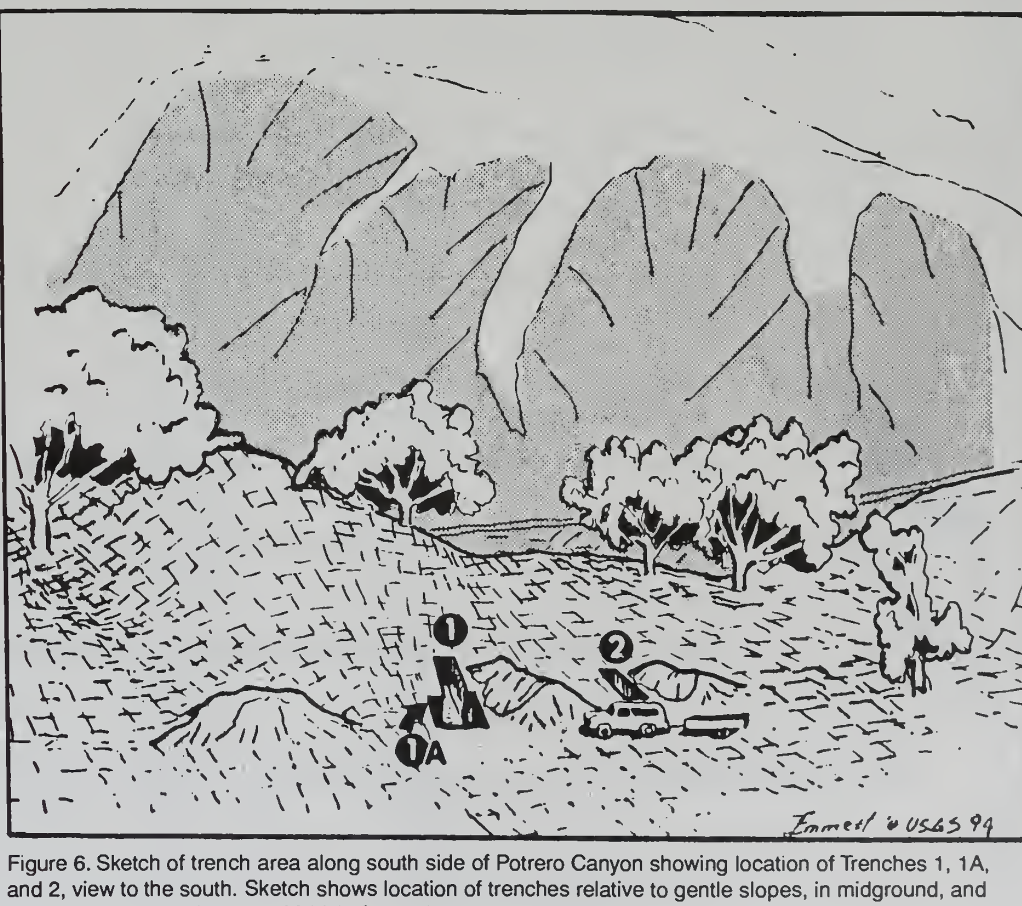
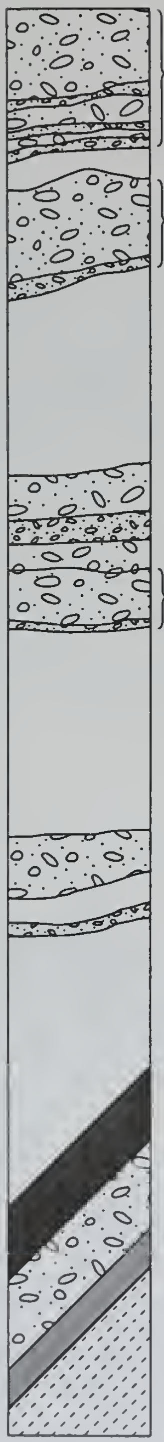


Figure 6. Sketch of trench area along south side of Potrero Canyon showing location of Trenches 1, 1A, and 2, view to the south. Sketch shows location of trenches relative to gentle slopes, in midground, and steep slopes, in background. Vehicle for scale.



UNIT	LITHOLOGIC DESCRIPTION
upper 1	Silty sand and pebble gravel, yellowish brown, poorly sorted; contains thin beds of laminated fine- to coarse-grained sand
2a & 2b	Silty clay loam to sandy clay loam (mudflow), grayish brown, poorly sorted
lower 1	Sandy gravel, moderately well sorted, poorly bedded, slightly better indurated than upper unit 1
3	Silty clay loam, grades downward to sandy clay loam and sandy loam (mudflow), very dark grayish brown, poorly sorted; 10–20% rounded pebble gravel, massive, well indurated. Note: units 2 and 3 grade uphill into colluvium
4	Sandy pebble gravel, yellowish brown, well sorted, loose
5	Silty gravelly sand, grayish-brown, poorly sorted, well indurated (mudflow)
6a	Sandy gravel, well sorted, loose
6b	Silty sandy gravel, well indurated, poorly bedded
7	Gravelly clay loam, grades downward into gravelly sand clay loam (mudflow), dark grayish brown, poorly sorted, well indurated, massive
8	Sandy gravel, moderately well sorted. Upper part is cobbly
9	Silty clay loam (mudflow), grayish brown, poorly sorted
10	Pebble gravel, moderately well sorted
11	Silty clay loam, dark grayish brown, poorly sorted, 10–20% rounded pebble gravel
	PICO FORMATION
	Sandstone, well-sorted, white to light gray , fine- to coarse-grained, slightly weathered to fresh, very closely to moderately fractured
	Conglomerate, moderately to well lithified, slightly weathered, closely to moderately fractured
	Sandstone, well sorted, very fine- to fine-grained, laminated, slightly weathered
	Mudstone, dark grayish brown, moderately well lithified, slightly weathered, closely fractured

Figure 7. Schematic stratigraphic section and lithologic description of units mapped in Trenches 1, 1A, and 2.

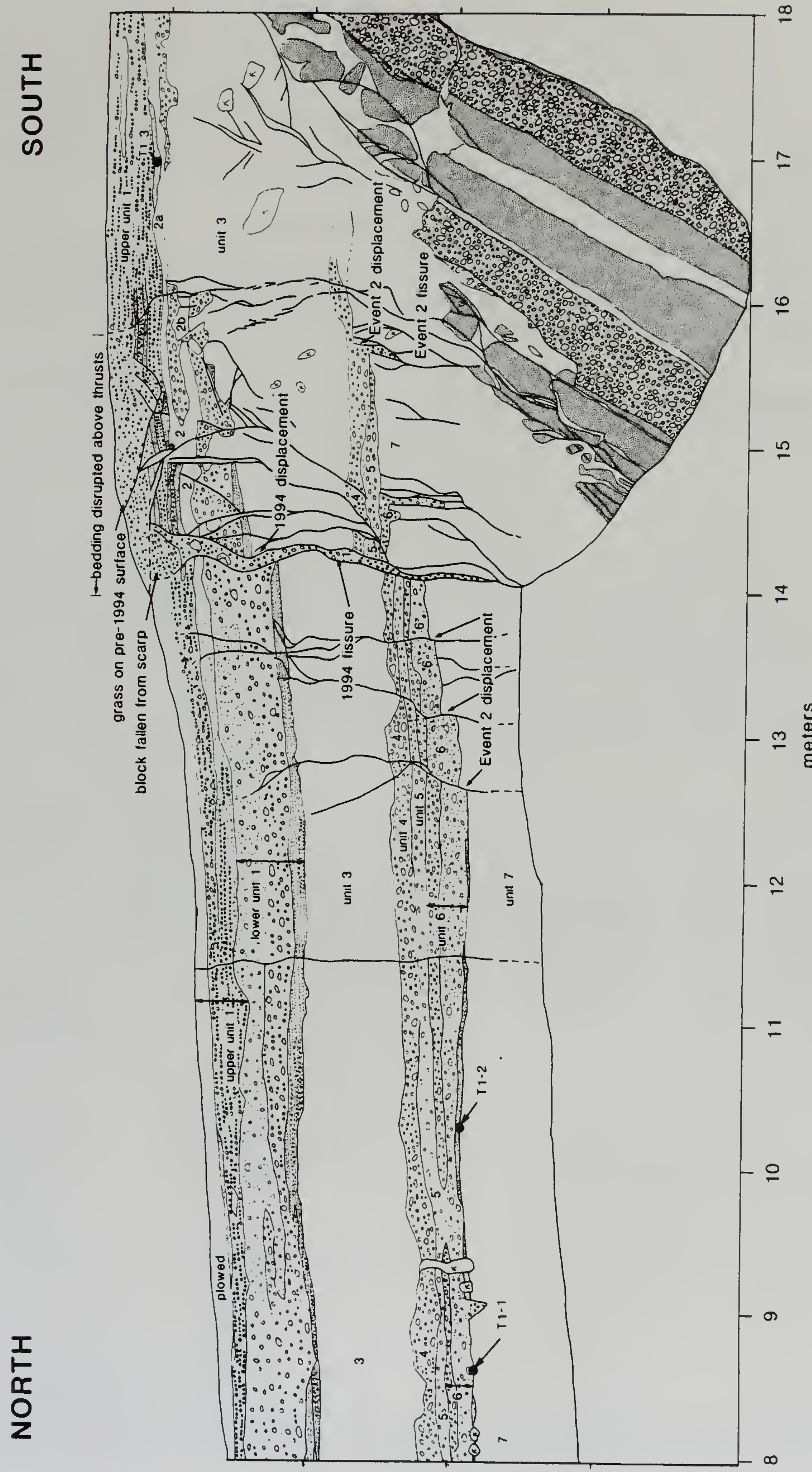


Figure 8. Log of Trench 1, east wall, in Holocene fluvial deposits and steeply dipping Pico Formation on south side of Potrero Canyon (see Figures 4 and 6 for location). See Figure 7 for description of units. Large solid dot, ^{14}C sample locations (see Table 1); K = krotovina (rodent burrow). See text for description of event horizons and event displacement.

here is unusual in that the Pico Formation exposed elsewhere in Potrero Canyon consists dominantly of siltstone and fine-grained sandstone. Overlying the bedrock is a sequence of interbedded middle to late Holocene slopewash, fluvial, and mudflow deposits. A composite stratigraphic section of material exposed in the trenches is shown in Figure 7. Trench 1 was excavated where the zone of deformation consisted of compressional failures developed along a 20-cm-high north-facing scarp. The trench was 25 m long and up to 5 m deep; a log of its midsection is shown in Figure 8. When we attempted to deepen Trench 1 to further expose the relation between the 1994 fractures and bedrock, part of the east wall collapsed. The log of the exposure created by the collapse is shown as Trench 1A (Figure 9). Trench 2 was excavated approximately 10 m to the west of Trench 1, across a 4-m-wide zone of primarily down-to-the-north surface fractures with individual vertical separations up to 10 cm. Trench 2 was 12 m long and locally as deep as 2 1/2 m (Figure 10).

Stratigraphy

The Holocene sedimentary units exposed in the trenches consist of two dominant sediment types: fluvial silty sand and sandy gravel that is interbedded with fine-

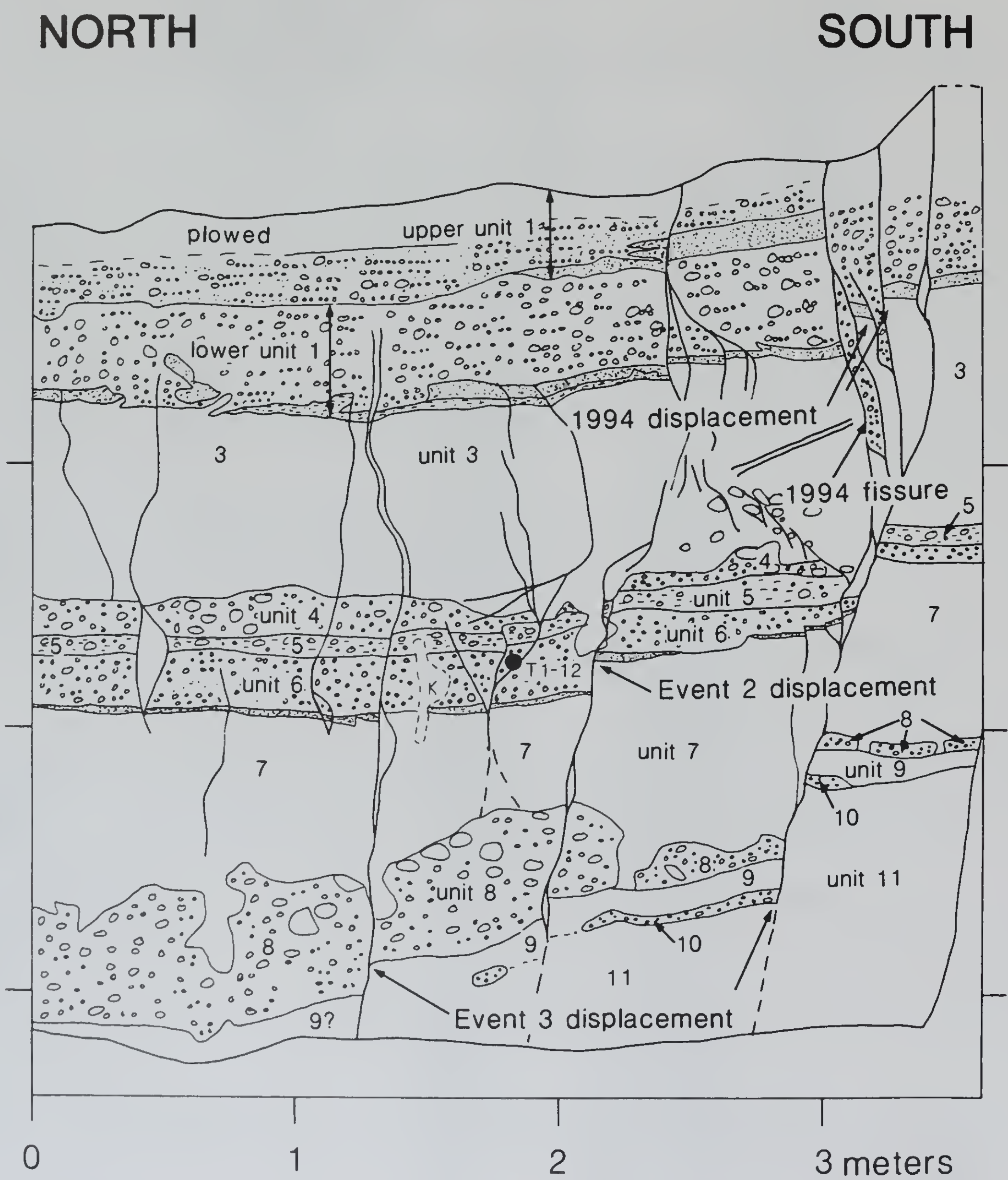


Figure 9. Log of Trench 1A, east wall, in Holocene fluvial deposits on south side of Potrero Canyon (see Figures 4 and 6 for location). See Figure 7 for description of units. Large solid dot, ^{14}C sample locations; K = krotovina. See text for description of event horizons and displacement.

Figure 10. Log of Trench 2 in Holocene fluvial deposits on south side of Potrero Canyon (see Figures 4 and 6 for location). See Figure 7 for description of units. Large solid dot, ^{14}C sample locations; K = krotovina. See text for description of event horizons and event displacement. *A*, east wall; *B*, west wall.

grained mudflow deposits. The mudflow deposits are massive; each mudflow probably represents a single depositional event. Alternatively, they may be composite flows from many storms. The lack of bedding in the mudflow units makes interpretation of depositional history difficult. For example, in Trench 1 unit 2 can be distinguished from unit 3 only where they are separated by gravel lenses.

The trench exposures also reveal erosion between depositional units. Erosion is most evident at the tops of sand and gravel beds prior to deposition of mudflows. For example, in Trench 2 unit 8 is scoured; higher in the section, unit 4 is locally removed and the top of unit 5 is irregular (Figure 10).

Subsurface Geometry of the Ground Cracks

The main structures exposed in the trenches are vertical to steeply (65°–80°) north-dipping fractures. In Trenches 1 and 1A (Figures 8 and 9), these are distributed across a zone up to 4 m wide. Within this zone, most of the net down-to-the-north vertical separation of 26 cm due to the 1994 Northridge earthquake occurs along a single trace (Trench 1, meter 14; Trench 1A, meter 3). In Trench 2 (Figure 10), the total 1994 displacement is smaller, 12–16 cm, and displacement is distributed across a 4-m-wide zone. Infilled fissures are a common feature of the 1994 deformation. For example, a fissure up to 25 cm wide and extending to a depth of 1.6 m below the surface is present in the main displacement zone (Figure 8). It is filled with sandy gravel derived from upper unit 1. Several small infilled 1994 fissures are also observed in Trench 2 (Figures 10*A* and 10*B*).

The excavations also expose the compressional fractures. It is apparent that these are shallow failures. Some compressional fractures are concave upward; others steepen with depth and abut high-angle extensional fractures, resulting in shallow decoupled blocks. In Trench 1, upper unit 1 is thrust north along two fracture traces across the top of the main 1994 fissure, sealing it off (meters 14–15, Figure 8). Thus, the compressional failures represent the last phase of surface deformation, forming after the extensional fractures.

North-dipping sandstone and conglomerate beds of the Pico Formation are exposed in the south end of Trench 1. The contact between the bedrock and unconsolidated deposits is irregular; colluvium is found between bedding planes and around isolated blocks of the Pico Formation. Between meters 14 and 16, several 5- to 10-mm-thick planar to curvilinear clay seams that generally parallel bedding are observed in the bedrock. There is no clearly defined faulting in the bedrock, but between meter 15.5 and 16 a set of closely spaced fractures, one of which is associated with displacement of unit 4, can be traced through the alluvium into the clay seams. Prior to the partial collapse of the east wall of Trench 1, the main fracture was observed to extend into a narrow clay-filled shear zone along the bedrock-alluvium contact, which itself is oriented subparallel to the bedding in the Pico Formation.

Evidence of Prior Displacements

The trenches at this locality expose evidence for at least two deformation events prior to the 1994 earthquake. Observations include buried fissure infills, larger displacement of older stratigraphic units relative to younger units across individual fractures, and upward termination of fracture traces. Because the fracturing is en echelon and slip varies in amount along strike, the subsurface displacement pattern from a single event can appear quite variable in trench exposures. Also, there is an undetermined, but probably small, component of slip that moved material through the plane of the trenches. A further complication is that deformation of the uppermost stratigraphic unit is not entirely brittle. For example, displacement in Trench 2 at the ground surface appears much greater than the displacement at the top of unit 3 due to infilling of fissures and backtilting (meter 6, Figure 10*A*). For these reasons, several types of observations are required to define an event horizon.

Evidence of the penultimate event (Event 2) is found in each of the trenches although there is some ambiguity as to the exact placement of the event horizon. In Trench 1 (Figure 8) pebbly sand from unit 4 is vertically displaced and fills a small fissure at meter 15.8, but the fracturing does not appear to extend into unit 3. Between meters 13 and 14 three fractures displace deposits as high in the section as the base of unit 3. Two of the fractures displace the contact between units 3 and 4 and the north fracture separates the base of unit 5, but not the unit 4-unit 5 contact. Each of these was reactivated as a fracture without displacement during the 1994 earthquake. In Trench 1A (Figure 9), a fracture at meter 2, which is correlative with the Trench 1 fractures at meters 13–14, displaces units 6 through 4 by approximately 12 cm. In contrast, the 1994 displacement, as expressed in upper and lower unit 1, is 4 cm. The penultimate event is well expressed in Trench 2 (Figure 10). At meter 4 on the east wall (Figure 10*A*), the contact between units 5 and 7 has a vertical separation of 15 cm. This fracture is discontinuous in unit 3, but the unit 3-unit 1 contact is displaced only 3 cm. On the west wall of the trench (Figure 10*B*), this same fracture is continuous through the complete section. Here, the contacts between units 5 and 7 and units 3 and 5 are both displaced 12 cm,

whereas the unit 3-unit 1 contact is displaced only 3 to 4 cm. Similar relations are also observed between meters 6 and 8. On the east wall, the fracture at meter 6 displaces the base of unit 3 and older units by 10 cm and the top of unit 3 by 4 cm (Figure 10*A*). Although these values are close, the west wall shows a larger difference with the base of unit 3 displaced 12 cm and the top of unit 3 displaced only 3 cm. At meter 7 on the east wall of Trench 2, the base of unit 4 is displaced 6 cm and this is associated with a fissure infill containing material from the lower part of unit 3. Reactivation of this structure in 1994 produced a graben at the surface with a net displacement of 3 cm. A similar relation is observed at meter 7.8 on the west wall where the base of unit 3 is displaced but not its top.

In summary, Event 2 is subtle at some locations, particularly where vertical separation is small, but is well defined at others. Individual displacements for the penultimate event are generally a factor of two to three larger than those that formed during the 1994 earthquake. There is some uncertainty as to the exact location of the Event 2 horizon. We favor the interpretation that it is at the top of unit 4, based particularly on the presence of infilled fissures. The event would have been followed by deposition of unit 3 and reactivation of some fractures in 1994. This would explain some of the sharp steps at the base of unit 3. Alternatively, the lower part of unit 3 was present prior to the penultimate event and the earthquake horizon is within unit 3. This would imply that unit 3 consists of multiple mudflows. The event horizon could even be at the top of unit 3, but this would require extensive erosion prior to deposition of higher units and would contradict evidence of fissure infills at the base of unit 3.

Evidence for the third event back is primarily from Trenches 1A and 2 (Figures 9 and 10). In Trench 1A, displacement across the main fracture, from the surface through the top of unit 7, is consistently about 21 cm (meter 3, Figure 9). All of this occurred in 1994. The net displacement across this zone along the base of unit 7 and in units 8 through 10 is 42–45 cm. This is approximately double the 1994 value and the difference is an expression of Event 3. At meter 1.3, the base of unit 8 is displaced 10 cm, but higher units do not appear to be affected. In Trench 2 (Figure 10), unit 8 is truncated by a fracture at meter 2 and the break extends through unit 7, but does not displace the top of unit 7. The event horizon is tentatively assigned to the top of unit 8.

Radiocarbon age control

The timing of depositional and deformational events in the southwest part of Potrero Canyon is constrained by radiocarbon analyses of eight detrital charcoal samples taken from the trenches (Table 1). Two very small samples of charcoal from the base of unit 6 in Trench 1 (Figure 8), about 0.5 m below the Event 2 horizon, were analyzed. These samples yielded calibrated ages of 367–1291 A.D. and 3109–2463 B.C. Six larger samples of detrital charcoal were collected from the lower part of unit 3 (mudflow) and the upper part of unit 7 in Trench 2 (Figure 10). The radiocarbon dates for units 3 and 7 are stratigraphically consistent and suggest the older sample from unit 6, Trench 1, is reworked from older deposits. Calendar dates are calculated from the weighted averages of the radiocarbon dates from units 3 and 7. The calibrated average of samples from unit 3 range in age from 1027–1235 A.D. Two calendar ranges are possible for unit 7, 897–908 and 959–1193 A.D. Because the age ranges from units 3, 6, and 7 overlap, we quantitatively refined the calibrated dates using the method of Biasi and Weldon (1994). If the Event 2 horizon is at the top of unit 4, then the radiocarbon dates from units 6 and 3 bracket the event. This suggests Event 2 occurred during the period 880–1280 A.D. If the event horizon is located in the lower part of unit 3, the timing of the event would still be constrained by the radiocarbon ages. However, if the event horizon is stratigraphically higher and unit 3 is composed of multiple flows, then we have little control on the age of Event 2. An alternative interpretation of the radiocarbon dates from units 3, 6, and 7 is that all the samples are reworked from an older burn and, thus, the deposits are actually younger. Additional trench exposures are being studied and more radiocarbon samples are being analyzed to test these possibilities.

At present, we have no radiocarbon age control for Event 3. However, the absence of soil development on units 8 through 11, below the Event 3 horizon, suggests the sedimentary sequence unconformably overlying the Pico Formation was deposited in the mid- to late Holocene.

Table 1. Calculated dates from ^{14}C analysis of detrital charcoal.

Sample	Stratigraphic Unit	^{14}C age* (yr B.P. ± 1σ)	Mean ^{14}C age§ (yr B.P. ± 1σ)	Calendar age‡ (yr A.D. ± 2σ)
T2-2	3	900 ± 50		
T2-6	3	900 ± 60	900 ± 30	1027–1235
T2-14	3	900 ± 50		
T1-1**	6	4230 ± 80		3109–2463 B.C.
T1-2**	6	1210 ± 160		367–1291
T2-13	7	1040 ± 60		
T2-17	7	970 ± 60	997 ± 35	897–908 959–1193
T2-18	7	970 ± 60		

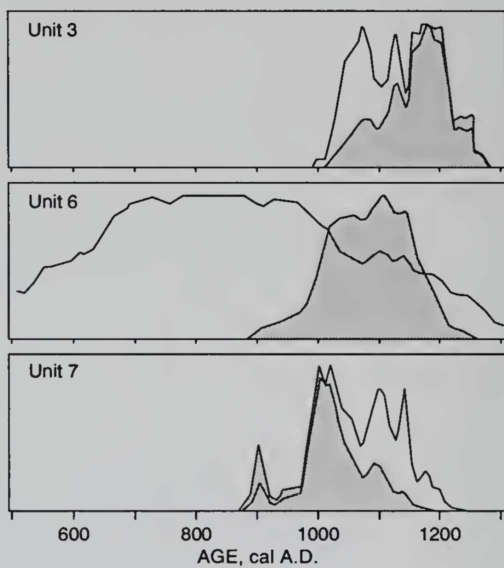
Note: Samples were analyzed at Lawrence Livermore National Laboratory and IsoTrace Radiocarbon Laboratory, University of Toronto (marked with double asterisk (**)), using accelerator mass spectrometry.

* Calculations assume a Libby half life of 5568 yr. Sample and standard $d^{13}C$ values are normalized to -25‰. Uncertainties are 1 standard deviation counting errors.

§ Weighted average.

‡ Dendochronologically calibrated, calendar age ranges from program of Stuiver and Reimer (1993), Method B, 20-yr calibration curve, 1.6 error multiplier. Two age ranges shown for unit 7 because two peaks are probable at 2σ.

Probability density functions for the calibrated mean radiocarbon dates of samples from units 3, 6, and 7 are shown to right with the horizontal axis in calendar years A.D. and the vertical axis in relative probability per year. Solid line represents radiocarbon density functions based on program of Stuiver and Reimer (1993); shaded peaks indicate quantitatively refined radiocarbon density functions based on technique of Biasi and Weldon (1994).



DISCUSSION

Potrero Canyon is located near the up-dip projection of the thrust fault that caused the Northridge earthquake. Observations of compressional fractures along the south side of the canyon led to early speculation that the ground deformation seen here may have been the result of primary tectonic faulting.

Our surface and trenching investigations indicate that primary faulting did not occur at Potrero Canyon. Stratigraphic and structural relations exposed in the trenches on the south margin of the valley are consistent with surface displacements resulting from differential settlement and lurching due to strong ground motion with movement taking place largely along the bedrock-alluvium contact, but possibly also involving the soft uppermost part of the bedrock. The distribution and types of earthquake-induced features found in Potrero Canyon are also generally consistent with deformation due to strong ground motion rather than to surface faulting. Specifically, we conclude that the surface fractures likely formed in response to strong shaking that resulted in alluvial compaction. The net down-canyon motion of the alluvial canyon fill supports this model, as does the presence of localized liquefaction, pipe breaks, and better developed crack sets on the western (down-gradient) sides of ridge spurs.

Unusually high strong ground motions recorded 10–25 km north of the epicenter are suggestive of up-dip directivity during rupture of the earthquake (Wald and others, in press). A station at the east end of Potrero Canyon recorded a peak ground velocity of about 115 cm/sec; the width of the velocity pulse is nearly 2 sec. Such focusing of the energy at the up-dip projection of the causative fault may have contributed to the observed ground deformation in Potrero Canyon. Southwest-directed horizontal movement of a 70-percent full, 3,780-liter tank of soda ash, which moved 35 cm, and a transformer, which moved 5 cm (Figure 3), are further indications of the north-northeast-directed strong ground motions sustained in Potrero Canyon.

The dates of prehistoric ground-displacement events at Potrero Canyon may provide information on earthquake recurrence for the blind thrust that caused the Northridge earthquake. However, if the ground deformation is due solely to the intensity of strong ground motion, it is possible that earthquakes on other nearby faults may have produced the displacements attributed to the earlier events. Given the approximately 1000 years since the penultimate event in Potrero Canyon, the San Andreas fault, 40 km to the northeast, is an unlikely source. The recurrence interval for this part of the San Andreas is about 100–200 years (Sieh and others, 1989; Fumal and others, 1993); one would expect evidence of several more paleoearthquakes during the interval exposed in our trenches if the San Andreas Fault was a contributing source. For example, the great earthquake of 1857 apparently did not cause permanent deformation in Potrero Canyon. Nor do we see evidence of ground rupture from historic earthquakes on other nearby faults. An earthquake in 1893 produced Modified-Mercalli intensities of VI in Ventura and Los Angeles counties; local intensities of VII–VIII were reported near Saugus and Newhall Ranch (Townley and Allen, 1939; Toppozada and others, 1981). This event apparently was a local shallow shock (~M 5.4) that produced abundant landslides and intense shaking in Pico Canyon, about 6 km to the east-southeast of our trench site. Similarly, we see no evidence in our trenches for the 1971 San Fernando earthquake (M 6.6). Therefore, it seems unlikely that moderate-sized events on nearby faults produce permanent ground deformation at Potrero Canyon. It appears that the paleoearthquakes observed in Potrero Canyon are the result of events on the blind thrust which caused the Northridge earthquake or much larger events on other nearby thrust faults.

The significance of surface fractures formed in Potrero Canyon is readily apparent when considering the rapid urban expansion of the region. Our studies in Potrero Canyon illustrate the severe effects resulting from strong ground motions during a moderate-sized earthquake. In this light, understanding the cause and recurrence of the Potrero Canyon surface fractures and related earthquake-induced effects is a critical element in determining the earthquake hazards of the region.

ACKNOWLEDGMENTS

We thank the Newhall Land and Farming Company (especially Jim Harter and Marilyn Nelson) and Alan Seward, geotechnical consultant, for permitting us to work on their property and for excavating trenches during this study, respectively. We also thank S. Hecker and D.J. Ponti (U.S. Geological Survey) for constructive reviews of an earlier version of the manuscript. A.B. Tucker (San Jose State University) analyzed radiocarbon samples at Lawrence Livermore National Laboratory. M. Stuiver and P.J. Reimer (University of Washington) provided a copy of CALIB to calibrate ^{14}C dates; G.P. Biasi (University of Nevada at Reno) used unpublished programs to plot refined ^{14}C distributions shown in Table 1. Emmett Dingel (U.S. Geological Survey) drafted Figure 6. The work was supported by the USGS National Earthquake Hazards Reduction Program.

REFERENCES

Biasi, G.P., and Weldon, R., II, 1994, Quantitative refinement of calibrated ^{14}C distributions: Quaternary Research, v. 41, no. 1, p. 1–18.

Fumal, T.E., Pezzopane, S.K., Weldon, R.J., II, and Schwartz, D.P., 1993, A 100-year average recurrence interval for the San Andreas fault at Wrightwood, California: Science, v. 259, p. 199–203.

Hall, J., ed., 1994, Northridge earthquake January 17, 1994 – Preliminary reconnaissance report: Earthquake Engineering Research Institute, Oakland, Calif.

Hecker, S., Ponti, D.J., Garvin, C.D., Hamilton, J.C., 1995, Characteristics and origin of ground deformation produced in Granada Hills and Mission Hills during the January 17, 1994 Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, earthquake of January 17, 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. .

Jibson, R.W., and Harp, E.L., 1994, Landslides triggered by the 17 January 1994 Northridge, California Earthquake: Earthquakes and Volcanoes, v. 25, no. 1, p. 31-41.

Rymer, M.J., Treiman, J.A., Powers, T.J., Fumal, T.E., Schwartz, D.P., Ponti, D.J., Hamilton, J.C., Garvin, C.D., and Cinti, F.R. in press, Surface fractures formed in the Potrero Canyon, Tapo Canyon, and McBean Parkway areas in association with the 1994 Northridge, California, earthquake: U.S. Geological Survey Open-File Report, scales 1:4,000 and 1:6,000.

Sieh, K., Stuiver, M., and Brillinger, D., 1989, A more precise chronology of earthquakes produced by the San Andreas fault in southern California: Journal of Geophysical Research, v. 94, no. B1, p. 603–623.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215–230.

Toppozada, T.R., Real, C.R., Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes: California Division of Mines and Geology Open-File Report 81-11, Sacramento, 182 p.

Townley, S.D., and Allen, M.W., 1939, Descriptive catalog of earthquakes of the Pacific Coast of the United States, 1769 to 1928: Bulletin Seismological Society of America, v. 29, no. 1, p. 1–297.

Treiman, J.A., 1995, Surface faulting near Santa Clarita, Los Angeles County, California, *in* Woods, Mary C. and Seiple, W.Ray, eds., Northridge, California earthquake, January 17, 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. .

U.S. Geological Survey, and Southern California Earthquake Center, 1994, The magnitude 6.7 Northridge, California, earthquake of 17 January 1994: Science, v. 266, p. 389–397.

Wald, D.J., Heaton, T.H., and Hudnut, K.W., in press, The slip history of the 1994 Northridge, California, earthquake determined from strong-motion, GPS, and leveling-line data: Bulletin Seismological Society of America.

Winterer, E.L., and Durham, D.L., 1962, Geology of southeastern Ventura basin, Los Angeles County, California: U.S. Geological Survey Professional Paper 334, p. 275–366.

SECTION III

Structural Damage

Chittenden, Robert, 1995, Earthquake damage to welded/bolted steel special moment frame buildings *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 147-151.

EARTHQUAKE DAMAGE TO WELDED/BOLTED STEEL SPECIAL MOMENT FRAME BUILDINGS

by

Chittenden, Robert[1]

INTRODUCTION

The 1994 Northridge earthquake damaged both structural and non-structural components in a variety of building types throughout the Los Angeles area, as discussed in other sections herein. Perhaps the most alarming pattern of structural damage involved the brittle failures of beam-to-column connections in steel Special Moment Resisting Frames (SMRF'S). This unexpected damage has shaken structural engineers' confidence in the predictability of the performance of steel Special Moment Resisting Frames and the reliability of conventional welded flange/bolted web steel beam-to-column connections as prescribed by the Uniform Building Code.

The typical beam-to-column SMRF connection that was extensively damaged is shown in Figure 1. This connection is prescribed in Section 2710(g)1B of the 1991 Uniform Building Code (UBC). The prescribed connection detail requires that the beam flanges be welded to the column flanges with complete joint penetration groove welds and that the beam web be connected to the column flange by welding or high strength slip-critical bolts. The welded flange/bolted web is the most widely used as discussed below.

EXTENT OF DAMAGED SMRF'S

Over 120 buildings sustained damage to the beam-to-column joints in the steel Special Moment Resisting Frames. The damage was widespread geographically from near the epicenter at Northridge to as far south as Santa Monica (about 15 miles) and West Los Angeles, and as far north as Santa Clarita. The majority of the damaged steel Special Moment Resisting Frame buildings are located in the recently developed areas of San Fernando Valley. Similar, but less extensive, damage has been found in buildings in Santa Monica and West Los Angeles.

The size of damaged buildings ranges from one-story low rise Special Moment Resisting Frames to 27-story high rise Special Moment Resisting Frames, although the most damage seems to be concentrated in the low to mid-rise structures of six stories or less.

Most of the damage occurred to structures of recent design and construction (1984 and later), although buildings up to twenty years old have also experienced connection damage.

TYPES OF DAMAGE

To date (January 1995), damage has been found in the beam-to-column connections in over 120 steel Special Moment Resisting Frame buildings. Figure 2 indicates the types of damage. Damage can be classified into three categories: (1) brittle cracking failure or tearing of the beam web (Type G3); (2) failure adjacent to (Type W3 or W4) or within (Type W1 or W2) the complete joint penetration beam flange-to-column flange weld; and (3) brittle cracking failure in the column adjacent to the beam flange-to-column flange weld. The column damage may be minor cracking in the flange (Type C1), a "divot" of base material torn out of the column flange (Type C2), cracking completely through the column flange in the through-thickness (z axis) direction (Type

[1]Division of State Architect, Office of Regulation Services, Sacramento, California

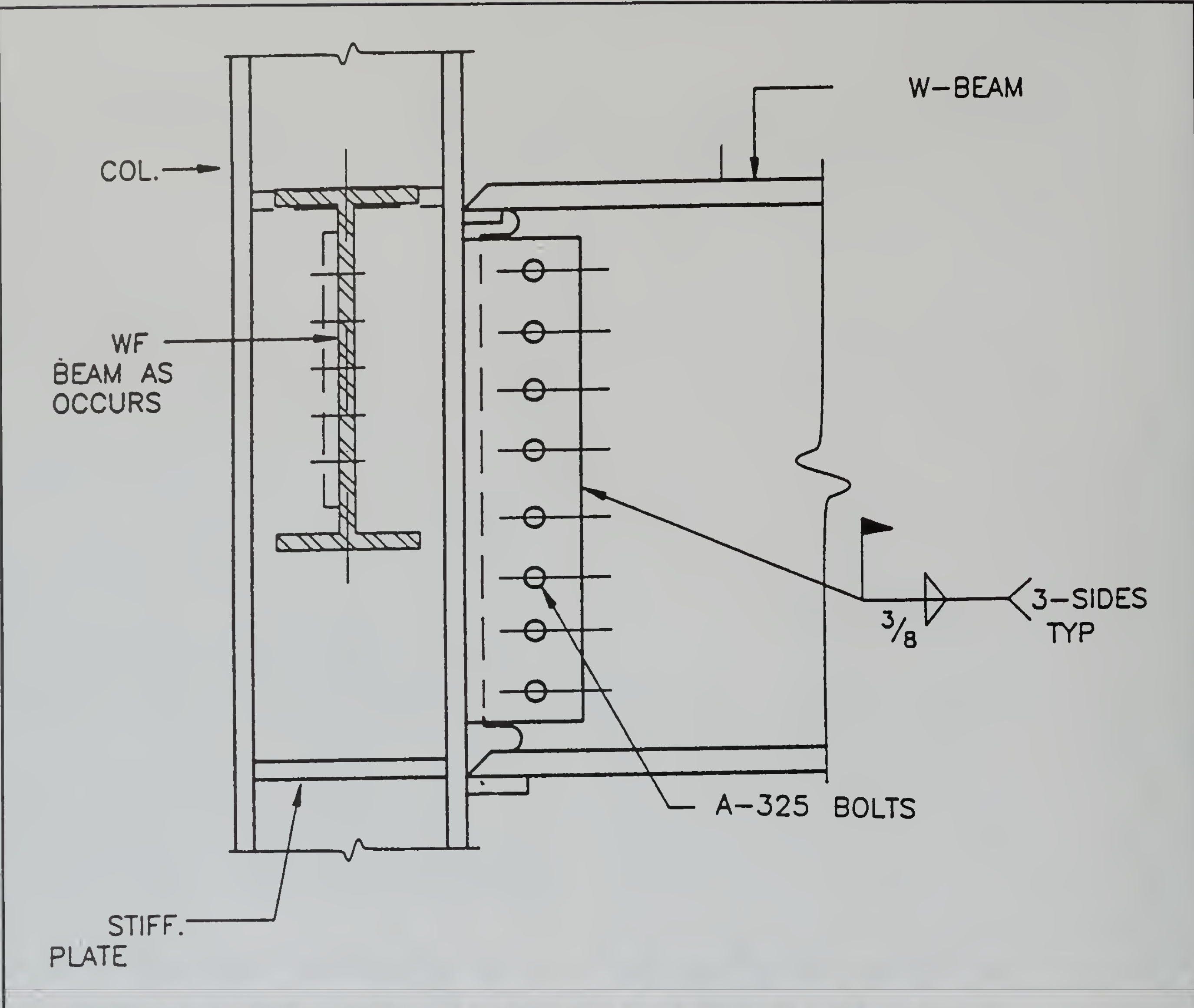


Figure 1. The beam-to-column connection as prescribed in Section 2710(g) 1B of the 1991 Uniform Building Code

C3 or C4), or cracking partially through the column flange parallel to the rolling (x axis) direction (type C5). In severe cases the crack will propagate from the flange into the column web (not shown) and in some rare instances, the column has been completely cracked across the entire column section.

The majority of this damage has consisted of brittle failure (fractures) at the beam bottom flange in the vicinity of or at the weld between the column and beam flanges. The majority of the failures are either cracking in the beam flange (Types G3) or failure adjacent to or within the complete joint penetration weld (Types W1 - W4). There have also been a large number of instances (approximately 15%) where failure occurred at the top flange. Top flange failures generally occur where there had been bottom flange damage. In some cases, damage at these connections included tearing and cracking of the column flanges and/or web (types C1-C5). Tearing of the beam shear tab connection (not shown) also occurred in a number of instances. Since the data on connection damage is still being collected, it is difficult to accurately determine any relationships between the type of damage and other parameters.

The primary conclusion that can be made is that the bottom flange connection is the most vulnerable location. This is probably caused by the following: (a) the discontinuity caused by the weld backing bar causes a stress riser; (b) the stress riser is at the point of highest strain in the beam flange; (c) any slab-beam interaction tends to lower the effective neutral axis, increasing the strain.

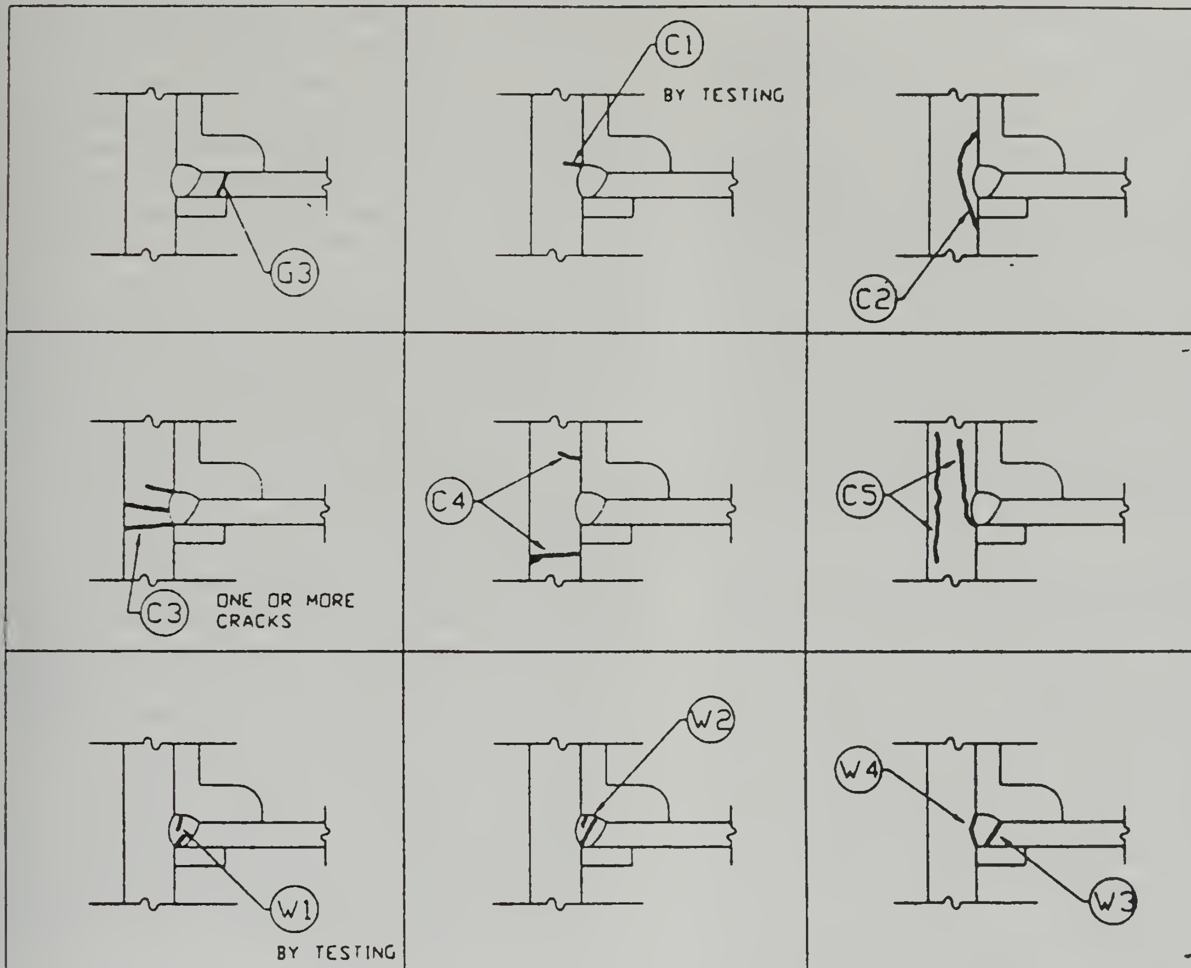


Figure 2. Types of damage found in beam-to-column connections in steel Special Moment Resisting Frame buildings. Type G3 illustrates brittle cracking, failure, or tearing of the beam web. Types W3 and W4 illustrate failure adjacent to the complete joint penetration beam flange-to-column flange weld, and types W1 and W2 illustrate failure within the complete joint penetration beam flange-to-column flange weld. Column damage is illustrated by Type C1–5.

UBC SEISMIC DESIGN PHILOSOPHY

Although the Northridge earthquake damaged other steel assemblies such as base plates and diagonal braces, by far the most common damage to steel structures was in the connections for Special Moment Resisting Frames. The seismic design philosophy inherent in the Uniform Building Code for Special Moment Resisting Frames assumes that, under strong ground shaking, the steel frame elements will be stressed beyond their elastic range. Inelastic behavior of the elements, which is useful in dissipating the earthquake energy transmitted to the structure, is allowed in elements capable of ductile behavior.

This design philosophy requires the beam-to-column connection to develop the strength of the beam, while allowing inelastic ductile behavior in the beam and/or column panel zones. To implement this philosophy, the Uniform Building Code requires that the connection strength be greater than the beam yield strength based on the specified yield strength of the steel. However, while the Code specifies the required connection strength, it does **not** quantify an inelastic rotation capacity.

Since the 1988 Edition, the Code has also included a prescribed detail that may be used without supporting calculations or testing. The typical connection using the prescribed detail is shown in Figure 1. The prescribed detail requires that the beam flanges be welded to the column flanges with complete joint penetration groove welds and that the beam web be connected to the column flange by welding or high strength slip-critical bolts. If the connection is an all welded connection with both the beam flange and web welded to the column flange, the beam must be temporarily bolted to the column during erection and prior to welding. Additionally, welding the web is more costly than high strength bolts. Because of these additional costs, the welded flange/bolted web

connection has become the detail of choice. This conventional welded flange/bolted web connection detail was in wide use throughout California for approximately 20 years prior to inclusion in the 1988 UBC.

The history of this welded flange/bolted web dates originally to the work of Popov and Stephen (1970). This investigation compared the performance of all welded connections to that of welded flange/ bolted web connections. Although the investigation showed that the welded flange/bolted web connections did not perform as well as the all welded connection and that the connection performance was somewhat erratic, these connections did develop substantial inelastic beam rotations. Hence, the welded flange/bolted web connection was accepted by structural engineers as being adequate for seismic applications.

The conclusions drawn from this investigation, coupled with the basic economy of the connection and an inherent developing trust in welding, led to such wide spread acceptance by structural engineers and fabricators that the welded flange/bolted web connection became fully accepted as the standard connection. This standard connection was codified and adopted into the 1988 UBC. Subsequent tests by Popov (1983), Krawinkler and others (1971), Bertero and others (1973), and Tsai and Popov (1988), and by Englehardt (1992), further demonstrated the variability of performance of these connections. Despite the lack of complete reliability of the connection as demonstrated in the tests, the number of failures at Northridge would have to be considered as very unexpected.

CAUSES OF CONNECTION FAILURES

Initially, the connection failures were blamed on a variety of causes: poor welding, high horizontal and vertical accelerations, poor construction practices, faulty steel, and other reasons. As the failures have been further investigated, the following factors are felt to be the primary contributors (Structural Engineers Association of California, 1994) to the unexpectedly poor performance of the prescribed connection:

1. Lack of knowledge of and unreliability of material properties. For example, A-36 steel beams typically have yield strengths far in excess of the specified strength. The mean yield strength of A-36 currently produced in the U.S is 49 ksi, or 33% higher than the specified value of 36 ksi. However, the range varies from 36 ksi to 72 ksi, or more than twice the specified strength. Further, the through thickness properties of flanges are not usually measured and are not well understood. However, for large column sections, this through thickness strength is often less than the specified yield strength. Hence, since the prequalified connection is designed based on specified yield strength, any overstrength in the beam and understrength in the column through flange thickness strength can lead to an understrength connection. Also, as steel is deformed inelastically beyond the yield point up to its ultimate strength, the steel gains additional strength or "strain hardens". This strain hardening must also be accounted for in the design.
2. The basic joint configuration not conducive to ductile behavior. The high restraint from the welded beam flanges and bending or tension in the column create a biaxial or triaxial tensile field. Steel does **not** behave in a ductile manner in the triaxial tensile stress state, but behaves in a brittle fashion.
3. Poor execution and quality control of welding. Welding for the prescribed connection must be in accordance with the American Welding Society "Structural Welding Code - Steel" (AWS D1.1). D1.1 requires the welder follow a "welding procedure specification," which describes and controls many variables such as welding process, type of electrode, welding machine voltage and amperage, electrode stickout, size and number of weld passes, preheat, and post-weld cool down. The D1.1 documents establish limits on these variable for "prequalified" welds, which are the type used for most structural welding. Many welds were executed without a weld procedure and violated many of the limits and requirements set forth in D1.1.
4. Large member sizes and large welds exacerbate the factors outlined above. In addition, the testing that established the viability of the prescribed connection was performed on much smaller members than currently in use today (particularly columns). It appears that extrapolation to larger sections of testing based on small sections should be done with great care.

EMERGENCY CODE CHANGES

As a result of the magnitude of the problem with the prescriptive connection, the International Conference of Building Officials (ICBO), upon petition by the Structural Engineers Association of California (SEAOC) and the California Seismic Safety Commission, took the unprecedented step of prohibiting the prescriptive joint by way of an emergency code change. Similarly, the California Building Standards Commission has adopted an emergency code change prohibiting use of the prescriptive connection for school, hospitals, state owned essential services buildings, and other state buildings.

A number of groups concerned with the design and construction of steel Special Moment Resisting Frame

buildings have begun work on determining the specific causes of the damage. The SEAOC, the Applied Technology Council (ATC), the consortium of California Universities for Research in Earthquake Engineering (CUREe), and the American Institute of Steel Construction (AISC) are working on solutions. SEAOC, ATC, and CUREe have formed a joint venture to attack the problem; the joint venture is termed the SAC Joint Venture. Limited testing has been completed at the University of Texas under AISC and private sponsorship, but much more is needed. The SAC Joint Venture will be conducting limited testing. Because of the preliminary nature of the available information, complete and definitive recommendations have **not** been published to date by any organization.

Since the data about the damage suffered by these buildings is still being collected, it is difficult to accurately determine the relationships between steel Special Moment Resisting Frame buildings affected by the Northridge earthquake and those in other areas. It is likely though, that very similar, if not identical, conditions are common in design and construction practices in other parts of the state and country.

REFERENCES

Bertero, V.V., Krawinkler, H., and Popov, E.P., Further studies on seismic behavior of steel beam-to-column subassemblages: Earthquake Engineering Research Center Report 73-27.

Englehahdt, M.D., 1992, Cyclic tests on large scale moment connections: University of Texas.

Krawinkler, H., Bertero, V.V., and Popov, E.P., 1971, Inelastic behavior of steel beam-to-column subassemblages: Earthquake Engineering Research Center Report 71-7.

Popov, E.P., 1983, Seismic moment connections for moment-resisting steel frames: Earthquake Engineering Research Center Report 83-02.

Popov, E.P., and Stephen, R.M., 1970, Cyclic loading of full size steel connections: Earthquake Engineering Research Center, Report 83-03, 70-3.

Structural Engineers Association of California Seismology Committee, 1994, Ductile steel beam-column joints – A discussion of preliminary observations, conclusions, and recommendations: Seismology Committee, October.

Tsai, K.C., and Popov, E.P., 1988, Steel beam column joints in seismic moment resisting frames: Earthquake Engineering Research Center Report 88-19.

Savage, W.U., 1995, Utility lifelines performance in the Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p.153-162.

UTILITY LIFELINES PERFORMANCE IN THE NORTHRIDGE EARTHQUAKE

compiled by

William U. Savage[1]

ABSTRACT

The Northridge earthquake provided a significant test of the ability of utility lifelines to provide adequate service to customers under severe seismic loading conditions. While this earthquake was not a worst case event, it did reveal that a moderate-magnitude earthquake occurring in an urban region can cause enough damage to modern, earthquake-cognizant utility systems to disrupt customer services and affect emergency response and initial recovery efforts.

INTRODUCTION

The study of recent earthquake effects on utility lifelines is a critical element in developing improved seismic design and construction procedures, devising system operational strategies to mitigate damage, and identifying areas in which more research is needed to improve the reliability and safety of these systems. For the utilities addressed in this chapter, extensive technical studies have been and are continuing to be conducted to maximize learning from the Northridge earthquake. Two publications in particular provide comprehensive and detailed documentation of damage and assessment of earthquake performance issues for these lifelines. These are the post-earthquake investigations coordinated and compiled by the Earthquake Engineering Research Institute in late 1994 (Hall, 1995); and the monograph on lifeline damage and system performance prepared by the Earthquake Investigation Committee of the American Society of Civil Engineers' Technical Council on Lifeline Earthquake Engineering (Schiff, 1995). A third important document is the California Seismic Safety Commission's Report to the Governor on the Northridge Earthquake (Seismic Safety Commission, 1995). This report includes summaries of the Northridge earthquake effects on utility lifelines and recommends actions ranging from policy and code changes to research and engineering applications, all with the goal of achieving improved seismic safety. These documents are referenced in the following sections, along with other studies that provide more details than can be presented in this chapter.

[1]Pacific Gas & Electric Company, San Francisco, California

GTE CALIFORNIA TELEPHONE SYSTEM

GTE California provides local telephone services to 3.5 million customers in the greater southern California area. About 400,000 of those customers located in the San Fernando Valley, Simi Valley, and Santa Monica areas had their GTE telephone service affected by the Northridge earthquake, with loss of service to 25,000 customers in the Pacoima area for a period of about 10½ hours. The total dollar cost of the damage was about $13 million. This section summarizes the physical damage caused by the earthquake to GTE facilities, the effects of that damage and other earthquake-related conditions on disruption and restoration of normal customer service, and the post-earthquake actions taken by GTE to further reduce the effects of future earthquakes.

Damage to GTE Facilities

The worst physical damage to telephone facilities consisted of structural and non-structural damage at four buildings:

- A leased office building in Santa Monica was seriously damaged. Fortunately the building was not occupied at the time, so there were no injuries. The building was subsequently abandoned.
- A leased building in Mission Hills that housed administrative functions was also damaged. Although the building was occupied by a small staff at the time of the earthquake, there were no injuries. The building repairs took about a year to complete.
- The central office in San Fernando received moderate damage. The building was not occupied at the time of the earthquake. The most significant effect to the office was damaged and leaking batteries, but the emergency generator performed well and the switching functions at the office were not impaired. The building was completely repaired in about 4 months.
- The Pacoima central office sustained moderate structural and non-structural damage, including damaged battery racks that resulted in leaking battery cases, damaged but operational relay racks, and the emergency generator sliding off its mounts. Although displaced, the generator started properly, but deformation in the cool air return allowed heat to build up to the point that the generator shut down. As at Mission Hills, the occupants of the Pacoima central office at the time of the earthquake were not injured.

Minor non-structural and cosmetic damage occurred in other GTE buildings, and cracking and other minor damage was found in some manholes and other underground facilities, but this additional damage did not significantly affect operations.

Customer Service Impacts

Following the Whittier Narrows earthquake in 1987, GTE had installed dynamic controls to enable priority service for police, fire, hospitals, and other emergency-response customers. In general, this system worked well in the Northridge earthquake. However, the very high numbers of calls attempted by both priority and normal callers created delays in establishing dial tone, typically of seconds but sometimes of up to three to four minutes. Callers often became frustrated waiting for the dial tone, and terminated their calls. Media announcements were provided to encourage customers to be patient in waiting for dial-tone access. But each strong aftershock produced a new flurry of calls and frustrating service congestion.

The lost primary and backup power systems at Pacoima took until 3 PM on January 17 to replace. The building had to be temporarily shored to provide safe ingress, and to connect a replacement generator. About 25,000 customers were disconnected from the telephone system until the Pacoima switch could be repowered. One of two GTE portable central office switching systems was set up at Pacoima as a backup, but it was not needed.

GTE experienced a significant increase in requests for new service connections for about eight weeks following the earthquake. Additional crews from other parts of the service territory were brought in to rapidly shift service connections from damaged or abandoned locations to temporary or permanent new ones for customers, including hospitals, commercial businesses, and residences.

Numerous GTE employees lived in the heavily damaged earthquake area and suffered home and property damage along with family care needs that disrupted their ability to rapidly report to work. In spite of these conditions, and in spite of a previously announced downsizing, the telephone personnel responded very well to the customer service needs. GTE established several monetary support programs to help employees begin their personal recoveries from the earthquake. These consisted of a quick $2,000 grant to people with earthquake damage, and an employee help fund with matching donations from other employees.

Preparations for Future Earthquakes

Although many of the earthquake preparations, such as annual emergency response exercises, that GTE had put into place paid off well in terms of generally high reliability and useability of their telephone system following the Northridge earthquake, additional actions were identified and have been largely implemented.

- Although previous effort had been placed into assuring good seismic performance of emergency power, the Northridge earthquake shaking was severe enough to damage batteries and a generator. Following the earthquake, a new design of battery rack was tested for high seismic resistance, and new racks have replaced the racks that failed. Racks of similar design will be used to upgrade battery racks elsewhere in the system.
- A three-year generator-mount upgrade program that was partly completed at the time of the earthquake was finished at the end of 1994. In addition, the type of fuel filter used for the standby fuel tanks was changed to one that will not clog if the sediment at the bottom of a fuel tank is disturbed by strong ground shaking. The generators continue to be started every two weeks, and placed under load every three months.
- An improved employee communication system has been set up, including a voice-mail facility, to communicate with employees immediately after the next earthquake and to check up on ones who have not been heard from. It is vital to quickly gain an assessment of the human resources able to help with the utility emergency response.
- GTE and Pacific Bell are near finishing conversion to a new switching system (called SS7 Control Network) that will better handle call congestion.

PACIFIC BELL TELEPHONE SYSTEM

Pacific Bell provides local telephone service to 3.8 million customers in the greater Los Angeles area. The telecommunications equipment required to support this network is located within 78 central offices spread throughout the service area. Fewer than 10 percent of these customers had their service directly affected by equipment problems caused by the Northridge earthquake, and these effects were brief.

Damage to Pacific Bell Facilities

Structural damage was sustained by 31 of the 78 central offices. Although no buildings collapsed, serious structural damage occurred at five locations No service outages or employee injuries occurred due to structural damage to the central offices.

Commercial power was lost in 22 central offices immediately after the earthquake. More than 24 hours after the earthquake, 14 offices were still operating on emergency generators. Only one central office went out of operation as a result of an emergency power failure, and it was restored within an hour.

Air conditioning problems occurred at five central offices as a result of damage to the cooling towers or a lack of water pressure to recharge the chilled water system. In offices where cooling problems were experienced, doors were opened and portable fans were used to circulate the air. No telephone service was lost due to equipment overheating.

In general, pre-earthquake installation of earthquake bracing and anchor bolts to protect equipment was successful. Strong shaking within some of the central offices caused a limited amount of equipment to fail, due to such effects as unseating of circuit boards, loosened connectors, and partial or complete failures of mechanical support and bracing of equipment and cabinets. All of the failed equipment in Pacific Bell's network was restored to service within a matter of hours following the earthquake.

As repairs have been carried out, additional damage has been discovered. No final damage figure is available (as of August 1995).

Customer Service Impacts

The largest impact to customer service came as a result of call congestion. On the day of the earthquake, call attempts into the Los Angeles area were 225 percent of normal. This call volume exceeded the capacity of the network, and controls were put in place to allow the maximum number of calls to complete without overloading the network. On the day of the earthquake 154 million calls were completed, representing a 110 percent increase in normal volumes. Call volumes did not return to normal until a week later.

Some customers lost telephone service due to damage to distribution cables or the telephone wiring within their homes. In the week following the earthquake, the company repaired 30,000 individual telephone lines, mostly in the San Fernando Valley. Overall, repair and installation work loads were 300 percent of normal for the first two weeks after the earthquake.

Network restoration activities were prioritized and coordinated through the Regional Emergency Operations Center (REOC). Emergency plans and disaster drills had prepared the members of the REOC. Communication was maintained between the REOC and key centers in Los Angeles using an emergency communications network that had been installed prior to the earthquake.

Preparations for Future Earthquakes

Earthquake preparedness will continue to be an integral part of Pacific Bell's role as a provider of telecommunication services. Diversity and redundancy are designed into the network to provide reliability. Central offices are built to exceed local building codes, and telecommunications equipment is anchored and braced. Central offices are equipped with both diesel generators and batteries as emergency sources of power. Personnel are trained in emergency procedures, and area-wide drills are held twice a year.

Pacific Bell plans to spend $100 million over the next seven years to strengthen the structural systems of 52 key buildings across California. These buildings include nine data centers and 43 central offices housing equipment that aggregates traffic moving across large geographic areas, or that provides telecommunications services for the emergency 911 system, military facilities, airports, governments, and "411" and "9" operators. Efforts under the seismic enhancement program include reinforcing sheer walls and increasing the structural support of critical mechanical systems such as air conditioners and lights.

By the end of 1996, Pacific Bell's Network Operations Centers in Sacramento and San Diego will be equipped to take over local network surveillance for each other. If one center is damaged, the remote facility can assess network problems in an earthquake-affected area and electronically reconfigure the network to do such tasks as reroute emergency calls to alternate answering points or reroute traffic around damaged facilities.

By the end of 1997, Pacific Bell will complete a $10 million installation of electronic sensors that can identify commercial power loss and start emergency generators in each one of the company's 680 central offices statewide. Within this same time frame, the company will complete another $10 million program to install connectors outside each central office statewide that will allow technicians to plug-in portable emergency generators to replace on-site generators that may be damaged during an earthquake. Technicians will no longer need to transfer cabling from damaged generators to portable units, a process that can take a minimum of 3 hours.

The number and geographical distribution of vendors who provide fuel for emergency generators will be increased. Also, a 1,000-gallon water truck and pump have been purchased for recharging chilled water cooling systems at sites where the water pressure has been lost.

ELECTRICAL POWER SYSTEMS

Approximately 2.5 million utility customers in southern California lost power after the earthquake, including everyone in the City of Los Angeles. Also, because of the interconnection of power grids, there were power outages in parts of the western United States and Canada. Outside of southern California, the most disruptive effect was in rural Idaho where 150,000 customers lost power for 3 hours.

Power was restored fairly quickly in all areas. The majority of southern California customers had power restored within 12 hours; approximately 93 percent had power within 24 hours; and virtually everyone had power within 72 hours. The major power systems in the area are operated by the Los Angeles Department of Water and Power (LADWP) and Southern California Edison (SCE), with some local areas served by municipal utilities. Total direct monetary losses were about $138 million to LADWP and $45 million to SCE (Schiff and others, 1995).

Damage to LADWP and SCE Facilities

There was significant damage to transmission substations, and two instances of collapsed lattice transmission towers. In general, power generation plants suffered little significant damage and were restored to service within a few hours to two days. Damage was relatively light to distribution substations and to the distribution system.

Although there was heavy damage to components at a few facilities, the majority of components at these same facilities performed well. The Northridge earthquake helped verify the ruggedness of some components, the benefit of good detailing and anchorage, and the effectiveness of recent seismic qualification and installation practices. The following is a list of observations on component performance:

- Dead tank and bulk oil circuit breakers of all voltages performed well. None were damaged, although they were present in substations that experienced measured peak ground acceleration levels as high as 0.93 g.
- Equipment in control buildings performed well. Control building equipment was generally well anchored and sustained little significant damage.
- In general, power plant structures and equipment performed well, verifying durability of power plant components, the effectiveness of present design criteria for these components, and the effectiveness of good detailing and anchorage. These facilities, however, were not subjected to the extreme high levels of ground motion.

- Retrofits for unanchored crossarm-hung pole-mounted transformers were very effective in preventing damage. There was a significant improvement in the performance of distribution transformers compared to the 1971 San Fernando earthquake.
- The vast majority of damage occurred to 500 kV, 230 kV, and 220 kV equipment. As has occurred during previous earthquakes, lower-voltage components performed well, although there was failure of cast aluminum connectors on some of the 34.5 kV bus structures. Some older 66 kV disconnect switches were damaged at the SCE Saugus substation. There was no equipment in the 115 kV voltage classification, therefore there was no verification of its assumed seismic ruggedness.
- The vast majority of lattice transmission towers performed well, as has been the case during past earthquakes. However, there were two instances of lattice tower collapses. These collapses were a surprise because they were the first ever experienced by the California utilities due to earthquakes. The collapses can be attributed to relative movement of the foundations. This indicates that the force levels used for tower design are probably adequate; however, some towers in landslide areas on ridge crests may be vulnerable to collapse during future earthquakes. The potential for damage needs to be considered in reviewing existing towers and locating new towers, and in emergency response planning
- Equipment that used composite bushings in lieu of porcelain performed well. Utilities are purchasing and installing more equipment that use composite bushings. Vendors are also using composite bushings to meet the higher seismic requirements that are being adopted as a result of past earthquake damage.

Customer Service Impacts and Utility Operations

Because the epicenter of the earthquake was within its service territory and within a few miles of several of its major facilities, LADWP was the electric utility most affected by the Northridge earthquake. LADWP is the largest U.S. municipal utility, with a service area that encompasses 465 square miles located within the city of Los Angeles. LADWP's power system provides electricity to approximately 1.36 million customers consisting of over 3.5 million people. Following the earthquake, all LADWP customers lost power. Sixty-three out of 221 LADWP facilities in the greater Los Angeles area experienced damage. The most significant damage was to Sylmar, Rinaldi, RS-J, and RS-U substations, which contain 500 kV, 230 kV and 34.5 kV AC equipment. Sylmar substation also contains DC equipment, which suffered extensive damage. Although there was extensive damage to some utility facilities, power was restored relatively quickly because of the redundancy in power systems and the efforts of utility personnel. The Northridge earthquake appears to have subjected the same substations that were affected by the 1971 San Fernando earthquake to higher acceleration levels. However, there was less damage during the Northridge earthquake due to upgraded seismic requirements and retrofits implemented after the San Fernando earthquake.

SCE's service territory surrounds the city of Los Angeles. SCE provides electricity to more than 4.1 million customers in central and southern California. Its 50,000 square mile service area has a population of nearly 11 million. Approximately 1.1 million SCE utility customers were affected by the Northridge earthquake. The major causes of SCE outages were damage at Pardee and Vincent substations, and tripping of Ormond Beach and Mandalay power plants. Electricity was restored to 0.5 million customers within 30 seconds and to virtually all other customers within 20 hours.

LADWP and SCE are among the most pro-active electric utilities in the area of mitigation of substation vulnerabilities, and both have had experience in restoration of service following earthquakes. Equipment has been purchased using the latest seismic requirements, and both utilities have been retrofitting and replacing vulnerable equipment. Yet both suffered significant damage and some customers had no electricity for up to several days. Therefore, the Northridge earthquake demonstrated that earthquake vulnerabilities still exist, even for the most up-to-date electric utility systems.

Preparations for Future Earthquakes

The earthquake highlighted areas of vulnerability where more work is necessary to strengthen components and improve the performance of electric systems.

There were numerous failures of transformer bushings in the voltage classification of 230 kV and 500 kV. Transformer bushings are probably the most significant remaining vulnerable component in most power systems, because of the inability to bypass transformers and the long repair and replacement time for bushings. Damage to bushings is likely to be a controlling factor in restoring power following future major earthquakes. LADWP, SCE, and Pacific Gas and Electric (PG&E) , in northern and central California, formed a task force prior to the Northridge earthquake to develop a program that would evaluate new and existing bushing with regard to breakage and oil leaks, and develop alternatives to improve the durability of bushings. Damage during the Northridge earthquake validated the need for this bush-

ing program. The IEEE 693 Substation Committee, which has broad participation by utilities, vendors, and consultants, is presently developing national guideline seismic specifications for transformers that will help ensure that new bushings are seismically rugged.

The following effects of the Northridge earthquake are being used to assess the effectiveness of present seismic requirements and previous mitigation efforts.

- Damage to transmission substations was the most significant factor in power outages. This has occurred during previous earthquakes.
- Porcelain damage to 220 kV, 230 kV and 500 kV AC and DC equipment was prevalent in damaged substations. Also, in general, the level of damage increased with increasing voltage level and age of the equipment. This also has occurred in past earthquakes.
- Damage occurred to some 230 kV and 500 kV equipment at measured peak acceleration levels as low as 0.15 g. Such damage has occurred at even lower acceleration levels during previous earthquakes. For electric systems that contain older vintage equipment and where ground motion attenuation is low, the geographic extent of substation damage could be very widespread.
- Interaction of equipment components played a major role in damage at the substations. Large relative movement between components and collapse of the adjacent components caused much of the damage. Utility companies need to consider this interaction when installing equipment and assessing the vulnerability of existing systems.
- A number of instrument transformers, disconnect switches, and other components that were qualified using dynamic analysis were damaged and did not perform as well as anticipated. Utilities have recognized before the Northridge earthquake that modeling assumptions in the dynamic analysis process often leads to optomistic estimates of the capabilities of substation equipment. Failures have occurred at much lower acceleration levels than calculated, generally because of damage to the brittle porcelain and cast aluminum components that are usually present in substation equipment. The west coast utilities have been specifying additional physical testing in lieu of dynamic analysis. The Northridge earthquake gave impetus and more justification to this change. National guidelines being developed by IEEE 693 will reflect the change from analysis to testing of components that have performed poorly during past earthquakes.

From the lessons learned, the ad hoc Inter-utility Seismic Working Group, the IEEE 693 Substation Committee, other organizations. and individual utilities are revising specifications, developing recommendations, and taking actions to mitigate the impact of future earthquakes on electric power service.

NATURAL GAS SYSTEM

The Southern California Gas Company (SoCalGas) operates a regional gas transmission system in southern California and provides gas service to nearly 4.7 million customers. Along with customer gas meters, the SoCalGas system includes 3,300 miles of steel transmission lines, 26,800 miles of steel and 14,900 miles of polyethylene plastic distribution pipe, five underground gas storage fields, and numerous above-ground gas operational facilities. There were approximately 151,000 gas service outages associated with the Northridge earthquake, primarily in the San Fernando Valley, with additional outages to the north in the Santa Clarita and Valencia areas and to the south in the western Los Angeles basin. More than 80 percent of these outages were due to customer-initiated service shutoffs, and about 10 percent involved leaks at customer-owned facilities. Whereas most repairs to damaged SoCalGas facilities were accomplished within a few days, it took almost a month to check and restore service to all customers. The total cost of earthquake damage to SoCalGas was about $60 million.

Damage to SoCalGas Facilities

The gas delivery system displayed a high level of integrity during the earthquake. Detailed statistics compiled by SoCalGas (1994) and reported to the California Public Utilities Commission, documented the damage to the gas system and to customer gas facilities.

Transmission pipelines. A total of 35 failures occurred along high-pressure transmission pipelines. These lines were of older construction, had been previously identified as potentially vulnerable to earthquake failure and included in a prioritized program of pipeline replacement. All modern (post-1941) transmission lines that were in the strong shaking and permanent ground deformation areas of the earthquake performed well.

- Two failures occurred in Line 120 (constructed in 1930) at the margins of a downslope lurch block displacement along Balboa Boulevard at the north edge of the San Fernando Valley. The pipeline failures occurred at welds. The failed portion of the pipeline was included in SoCalGas's pipeline replacement program. The replacement pipeline had been installed just prior to the earthquake and was scheduled to be connected within a few months following the date of the earthquake. The replacement line crossed the lurch block and was undamaged.

- Twenty-five failures occurred along 60-year-old Line 1001 located between Fillmore and Newhall north of the San Fernando Valley. All but one of the failures occurred at welds. The pipeline right-of-way lies in a region that experienced intense permanent ground deformation and strong ground shaking during the Northridge earthquake. This pipeline had been given a lower priority for replacement due to its remote location in an unpopulated area.
- The remaining eight failures occurred at several locations along two other 1930-31 vintage pipelines, and one 44-year-old pipeline at Aliso Canyon gas storage field.

Gas storage fields. Gas is stored in five underground reservoirs that were once used for oil production. Only the one at Aliso Canyon, just above the north end of the San Fernando Valley, was significantly affected by the earthquake. Along with a buckled and split high-pressure pipeline, damage included deformation of pipe supports, displaced gas injection and withdrawal lines, and structural damage to a large compressor fan unit. The underground storage field itself was undamaged, and the field was restored to operation in five days. Oil and water tanks were also damaged.

Distribution pipelines. The earthquake directly caused 154 leaks or failures in the steel distribution pipelines, including 80 damaged mains and 74 damaged services. The most vulnerable components of this system are older threaded joints and cast iron valves. There were 27 reported cases of earthquake damage to polyethylene pipes, with about half of the damage found at early fusion joints or older-style fittings. An additional 536 leaks were found that are also classified as earthquake-related. These leaks occurred in pipe or joints that were weakened by corrosion, material defects, construction defects, or unknown causes, with the earthquake activating or accelerating the weakness to cause a subsequent leak.

Meter set assemblies. A total of 6,461 leaks at meter sets were either reported by customers or found during post-earthquake leak surveys. Many of the leaks were of very small volume and did not pose an imminent hazard. Most of the leaks were due to bushing, gasket, and stopcocks within the meters. Field personnel estimated that approximately 20 percent of the leaks that were repaired were probably present prior to the earthquake. Additional common causes of leakage were debris falling on the meter set or physical damage due to flexing and twisting of the meter, in some cases associated with deformation or damage of the adjacent structure.

Damage to Customer Facilities

A total of 15,021 leaks at customer gas meters were found during service restoration following the Northridge earthquake (SoCalGas, 1994). Approximately 7,000 leaks occurred at appliance connectors, chiefly involving semi-rigid aluminum or copper connectors that are no longer being installed. As was true for meter sets, many of these leaks were very small and did not pose a significant hazard.

There were 8,985 damaged or separated gas appliance vent systems. Water heater toppling was the most common problem. SoCalGas service personnel reported 2,526 unstrapped water heaters that were damaged or leaking, while only 211 strapped water heaters were found damaged.

Approximately 9,100 customers suffered such significant property damage that service could not be restored within a month following the earthquake.

Customer Service Impact

Within an hour following the occurrence of the Northridge earthquake, SoCalGas had activated its Emergency Operations Center in downtown Los Angeles. Assessment of the safety of the system received first priority, followed by restoring service as quickly as possible. Customer-initiated shutoffs of services, and shutoffs necessitated by identified gas leaks either at customer facilities or in pipelines, totaled more than 151,000. SoCalGas responded to over 400,000 customer service calls following the earthquake.

Service recovery was carried out by SoCalGas's regular work force augmented by trained management employees, former service employees, and personnel from neighboring gas utilities in California and Nevada. A total of 3,400 personnel were involved at the peak of the recovery effort.

Service restoration involved three steps, which were carried out concurrently in the earthquake-affected area:

- Pipelines were surveyed using highly sensitive leak detectors. Reports of possible gas leaks from customers and emergency response personnel were given high priority in leak surveying.
- Meter-to-meter investigations were performed at customer facilities to evaluate the integrity of the meter set assembly, house lines, and appliance connections. Necessary repairs were carried out, or identified for future completion.
- When the service safety was assured, the service was relighted and checked.

Service was restored to approximately 84,000 customers within one week after the earthquake. By February 7, service had been restored to over 119,000 customers. Many of the remaining 32,000 customers had restored their own service or had hired a plumber do so.

At the time of the Northridge earthquake, seismic gas shutoff valves had been installed by customers at a number of residences and other facilities in the southern California area. SoCalGas personnel restored service to 841 facilities where seismic valves had to be reset. Leaking gas was found at 162 of these services. Strand (1995) reported on several industrial and educational structures where seismic valves tripped and where customer gas systems were damaged. He also reported that aftershocks tripped some valves multiple times, such as those at the Los Angeles Unified School District schools. Seismic valves tripped as far away as 48 miles from the earthquake epicenter.

There were 51 structure fires (not including mobile homes) reported following the earthquake. Information on these fires was gathered by SoCalGas personnel, the Los Angeles City and County Fire Departments, and other city agencies (SoCalGas, 1994). The following table summarizes the causes of the fires:

Water heaters	20
Other gas appliances	08
Broken interior gas lines	08
Broken gas meter set assemblies	02
Street fires (including five homes burned on Balboa Blvd.)	07
Cause unknown	06

The dominant cause of fires was damaged water heaters. The primary reasons appear to be inadequate or missing bracing or strapping, or weak or flimsy water heater legs.

Approximately 172 mobile homes were destroyed by fires. Two primary causes of the mobile home fires were failure of mobile home supports leading to breakage of gas risers, and breakage of interior gas lines due to overturning water heaters and other appliances.

Preparations for Future Earthquakes

The experience gained from the effects of the Northridge earthquake on gas system components confirmed the high level of earthquake resistance in the modern steel and polyethylene pipes. Other types of pipelines, such as high-pressure lines made with older welding methods and steel distribution piping using threaded joints and certain cast iron valves, are known to be vulnerable. Ongoing maintenance and special pipeline replacement programs are systematically reducing these problems.

Several areas for gas safety and improvement in reliability of customer-owned facilities need attention. These include seismic anchoring of water heaters and other appliances, and anchoring to secure mobile homes to protect the residents and contents. To some extent, current regulations provide for good earthquake performance, but a large residual problem exists in the already-built structures.

The role of seismically activated shutoff valves, excess flow valves, and "intelligent" valves that can detect dangerous coincident conditions of earthquake shaking and anomalous gas flow conditions need further investigation. SoCalGas is initiating a pilot seismic shutoff valve program for 20,000 customers in southern California. Pacific Gas and Electric Company and SoCalGas are participating in a technology development program for a new generation of intelligent gas meters. Beginning in late 1995, the California Public Utilities Commission will conduct a series of hearings and workshops designed to further evaluate the role of seismic valves, particularly for use at mobile home parks.

WATER AND WASTEWATER SYSTEM

The Los Angeles Department of Water and Power (LADWP) provides water in the San Fernando Valley; other utilities supply water in the Santa Clarita and Simi Valleys. The Metropolitan Water District of Southern California provides imported water from the State Water Project and the Colorado River to the water utilities in the affected areas. A small additional source of water comes from local water wells. The systems serve about 3.7 million people; about 15 percent had their water service affected by the earthquake, primarily in the San Fernando Valley. In the heaviest hit areas, customer service was disrupted for one to two weeks. The cost of the earthquake damage to the water system was about $44 million.

The municipal wastewater systems in the affected area all lost power to pumping stations following the earthquake, but emergency generators and sewage bypasses prevented spills. Minor to moderate damage occurred to water reclamation facilities, with more extensive damage to sewer lines, much of which did not immediately affect the use of the lines. The estimated cost of wastewater system damage is in excess of $36 million.

Damage to Water Facilities

Water Transmission Pipelines. Six large-diameter steel and concrete water-supply transmission pipelines broke during the earthquake, disrupting sources for water treatment plants serving the local water utilities. Steel

pipelines typically failed at lap-welded joints, and concrete pipelines also failed primarily at joints. The damage is attributed to permanent ground deformation or severe ground shaking. Repairs to the six supply pipelines were made in two days to two months, depending on sevice needs and system redundancy; three of the lines required additional permanent repairs that were completed in summer 1994. Also, transportation system damage and the resulting traffic congestion were factors in slowing the repairs. The transmission pipeline damage did not cause significant disruption of customer service, however, because rerouting and alternate supplies such as wells or reservoirs provided adequate supply until the initial repairs could be completed.

Large-Diameter Trunk Lines. About sixteen large-diameter trunk lines failed in the earthquake-affected region (Hamada and others, 1994). The most spectacular ruptures were the Granada and Rinaldi trunk lines, which suffered compressional and tensional failed joints due to the permanent ground displacement of about one foot that occurred along Balboa Boulevard in Granada Hills. Repairs took 12 days for the 48-inch Granada line, and 56 days for the 68-inch Rinaldi line. The other damaged trunk lines also were affected by ground displacement and required generally similar repairs.

Distribution Lines. Significant damage occurred to local water distribution systems. Approximately 1,400 leaks in mains and services were reported by LADWP, and the water utilities in the Simi and Santa Clarita Valleys reported 300 leaks. Older cast-iron pipes with rigid joints and older steel pipes weakened by corrosion were the predominant types of pipe that failed. Fire hydrants and air and vacuum valves also were broken. The repair process for distribution pipes was time-consuming, including draining and repairing the pipe, filling and testing the pipe, and repeating the process in the common occurrence of multiple leaks. Logistics to support the repair personnel was also a problem, due to limited power and water in the affected areas, and slow surface transportation.

Water Treatment Plants. No significant failures occurred to either water treatment or filtration facilities at the three operating plants in the region. The most significant damage occurred to gratings and wood baffles and was caused by shaking and sloshing in large water basins. A fourth water treatment plant under construction in Simi Valley had no damage.

Storage Tanks. Extensive damage occurred to older above-ground steel water tanks, with about 40 tanks rendered nonfunctional by the earthquake. Sloshing within the tanks caused roof damage, tank base and shell buckling, and damage to inlet-outlet piping. In contrast, post-tensioned concrete tanks, many of which were set at least partially below grade, performed well.

Customer Service Impacts

The earthquake damage led to two significant customer service impacts in the heavily damaged areas:

- The loss of fire suppression water put many neighborhoods at risk. Fire departments had to use water drafted from swimming pools or brought in by tanker trucks. Fortunately, wind was not a factor in spreading earthquake-related fires.
- Piped drinking water was unavailable for one to two weeks in some heavily damaged areas. In areas where water was available but of questionable quality, "boil water" notices were issued by water agencies in cooperation with the California Department of Health Services. As water quality was established, the notices were lifted, but the necessary repairs and testing took as long as 18 days in some areas. In the interim, emergency water supplies were provided by water and beverage companies and by many public agencies. Up to 72 tanker trucks were in use to deliver potable water in the San Fernando Valley.

Damage to Waste Water Systems

The sewer collection systems in the affected area generally performed well, but power outages for nearly eight hours and moderate damage to several reclamation plants impaired normal operations and caused immediate post-earthquake concern. However, standby generators, sewer bypasses, and effective use of available plant resources prevented sewage spills and adequately protected water quality.

Sewer line damage in some cases was quickly recognized, inspected using television probes, and was temporarily bypassed and quickly repaired. However, because sewer lines normally operate by gravity flow, damage may not be detected if flow continues. Additional post-earthquake inspections and occasional collapses have revealed more damage than was initially detected, and has necessitated a lengthy sewer line repair process.

Preparations for Future Earthquakes

The generally good performance of water and wastewater systems in the Northridge earthquake reflects the improvements in structures and equipment that resulted from the experience and modernized seismic codes and practices instituted following the 1971 San Fernando earthquake. The damage that occurred in the Northridge earthquake was primarily due to older (pre-1971) pipelines and facilities. Seismic upgrades of the large remaining inventory of such components requires effective planning, budgeting, and financing. The Seismic Safety Commission (1995) has recommended the development

and implementation of programs in each water utility in California to identify and address the utility's seismic risk.

Extensive information has been and will continue to be developed from the observations of good and poor performance of various types of water system components and facilities, and effective and ineffective emergency response measures. The application of this information is needed to revise standards, codes, and practices for improved earthquake performance. Some of the water utilities, such as LADWP, are leaders in the industry in terms of identifying and implementing such seismic vulnerability mitigations.

ACKNOWLEDGMENTS

The sections of this chapter were prepared by or included significant contributions from the following individuals:

William Chubb, Pacific Bell; Susan Clay, GTE California; Richard Gailing, Southern California Gas Company; LeVal Lund, Civil Engineer; Edward Matsuda, Pacific Gas and Electric Company; and Dennis Ostrom, Southern California Edison.

REFERENCES

Hall, J., 1995, Northridge earthquake of January 17, 1994, reconnaissance report volume 1: Earthquake Spectra, Supplement C, Volume 11, 510 p.

Hamada, M., Tazoh, T., Iwamoto, T., Suzuki, N., Ejiri, J. and Ohtomo, K., 1994, Damage to water pipes during the 1994 Northridge earthquake *in* O'Rourke, T. D. and Hamada, M., eds., Proceedings from the Fifth U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, Technical Report NCEER-94-0026: National Center for Earthquake Engineering Research, Buffalo, New York, p. 717-729.

Schiff, A., 1995, Northridge earthquake – lifeline performance and post-earthquake response: Technical Council on Lifeline Earthquake Engineering, American Society of Civil Engineers, Monograph 8.

Seismic Safety Commission, 1995, Northridge earthquake – turning loss to gain: Report to Governor Pete Wilson, SSC Report No. 95-01, Sacramento, California.

Southern California Gas Company, 1994, Northridge earthquake gas delivery system integrity study: Report prepared for the California Public Utilities Commission.

Strand, C., 1995, Gas leaks, gas-related fires, and performance of seismic gas shutoff valves during the Northridge earthquake: Proceedings, 4th U. S. Conference on Lifeline Earthquake Engineering, American Society of Civil Engineers, p. 692-699.

Yashinsky, M., 1995, Damage to bridges and highways from the Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p.163-185.

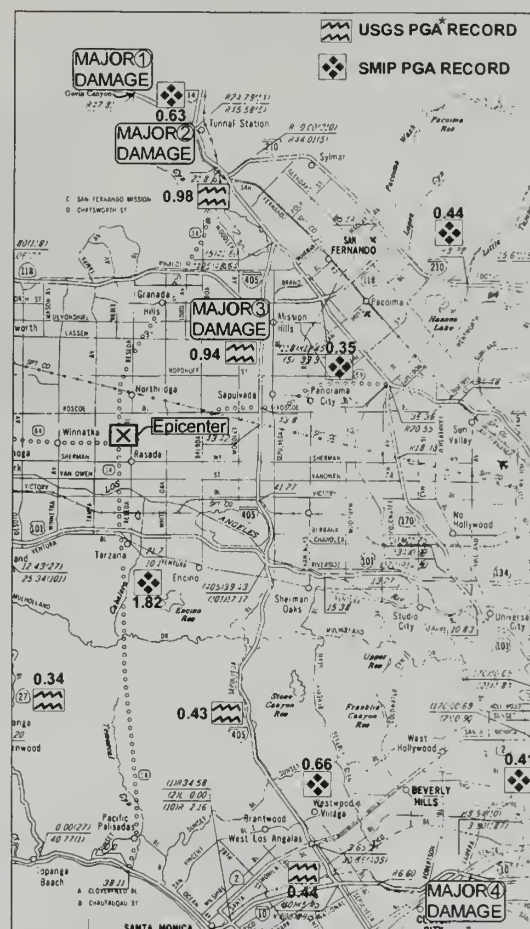
DAMAGE TO BRIDGES AND HIGHWAYS FROM THE NORTHRIDGE EARTHQUAKE

by
Mark Yashinsky[1]

OVERVIEW

There are approximately 12,000 State Highway Bridges in California. About 1,200 of these bridges were in the area that experienced ground accelerations greater than 0.25 g during the Northridge earthquake. Most of these bridges performed well during the earthquake. Bridges constructed to Caltrans' current seismic specifications survived the earthquake with very little damage. Seven older bridges, designed for a smaller earthquake force or without the ductility of Caltrans' current design, sustained severe damage during the earthquake. Figure 1 shows the four locations where severe bridge damage occurred during the Northridge earthquake. Table 1 identifies these severely damaged bridges that were replaced after the earthquake. Another 230 bridges suffered some damage ranging from serious problems like column and hinge damage to minor problems such as concrete cracks, bearing damage, or approach settlements. Table 2 identifies all state highway bridges that were damaged during the earthquake (see p. 168).

After the earthquake, maintenance crews closed many of the major interchanges in the Los Angeles area. After the interchanges were inspected for damage they were reopened. Many were reopened after shoring was placed under them. This was because of concerns about hinge damage. The earthquake struck early in the morning when traffic was light; therefore, there were few injuries and only one fatality related to bridge and highway damage.



*PGA (Peak Ground Acceleration).

Figure 1. Locations of severe damage to bridges from the Northridge earthquake.

Table 1. Bridges severely damaged by the Northridge earthquake.

Bridge Location	Bridge Name	Bridge #	Yr Built	Length	Type
1) Gavin Canyon (I-5)	Gavin Canyon Bridge	53-1797R/L	1967	741 ft	QBC CBC*
2)14/5 Interchange	Rte 14/5 Sep. & OH	53-1960F	1971-74	1582 ft	QB CBC
	North Connector OC	53-1964F	1971-74	1532 ft	QBC CBC
3) 118 west of 405	Mission Gothic UC	53-2205	1976	532 ft	QBC
	Bull Creek Cyn Ch Br	53-2206	1976	256 ft	QBC
4)I-10@ downtown	La Cienega-Venice UC	53-1609	1964	871 ft	CBC
	Fairfax-Washington UC	53-1580	1964	577 ft	CBC

* QBC - cast in place prestressed box girder continuous; CBC - concrete box girder continuous.

[1] California Department of Transportation, Office of Earthquake Engineering, Sacramento, California

GAVIN CANYON

This is the northernmost location of severe bridge damage (Figure 2, Photo1). The bridges carry north and south traffic over Gavin Canyon on Interstate 5 through steeply mountainous terrain. At the bridge site there are approximately 20 feet of sand above a rock layer of siltstone and shale with tall structural fills supporting the abutments. The area is 9.2 miles from the epicenter of the Northridge earthquake and near the surface projection of the Oak Ridge -Newhall Fault. Ground motion records indicate strong shaking in this area with a peak horizontal acceleration of about 0.8 g.

Structure

These extremely tall, highly skewed bridges are on I-5, 2 miles north of the 14/5 Interchange. They were composed of three frames. The end frames were reinforced concrete box girders that were supported on one end by diaphragm-type abutments and cantilever over two column bents. The center frame was a prestressed concrete box girder on four columns (two bents) that supported the cantilever spans of the end frames. All the columns had 6 foot-3 inch by 10 foot octagonal sections with fixed ends and a flare on top. The bridges were retrofitted in 1974 with restrainer cable units at the 8-inch hinges that connected the three frames together.

Photo 1. Damage to Gavin Canyon bridges due to the Northridge earthquake.

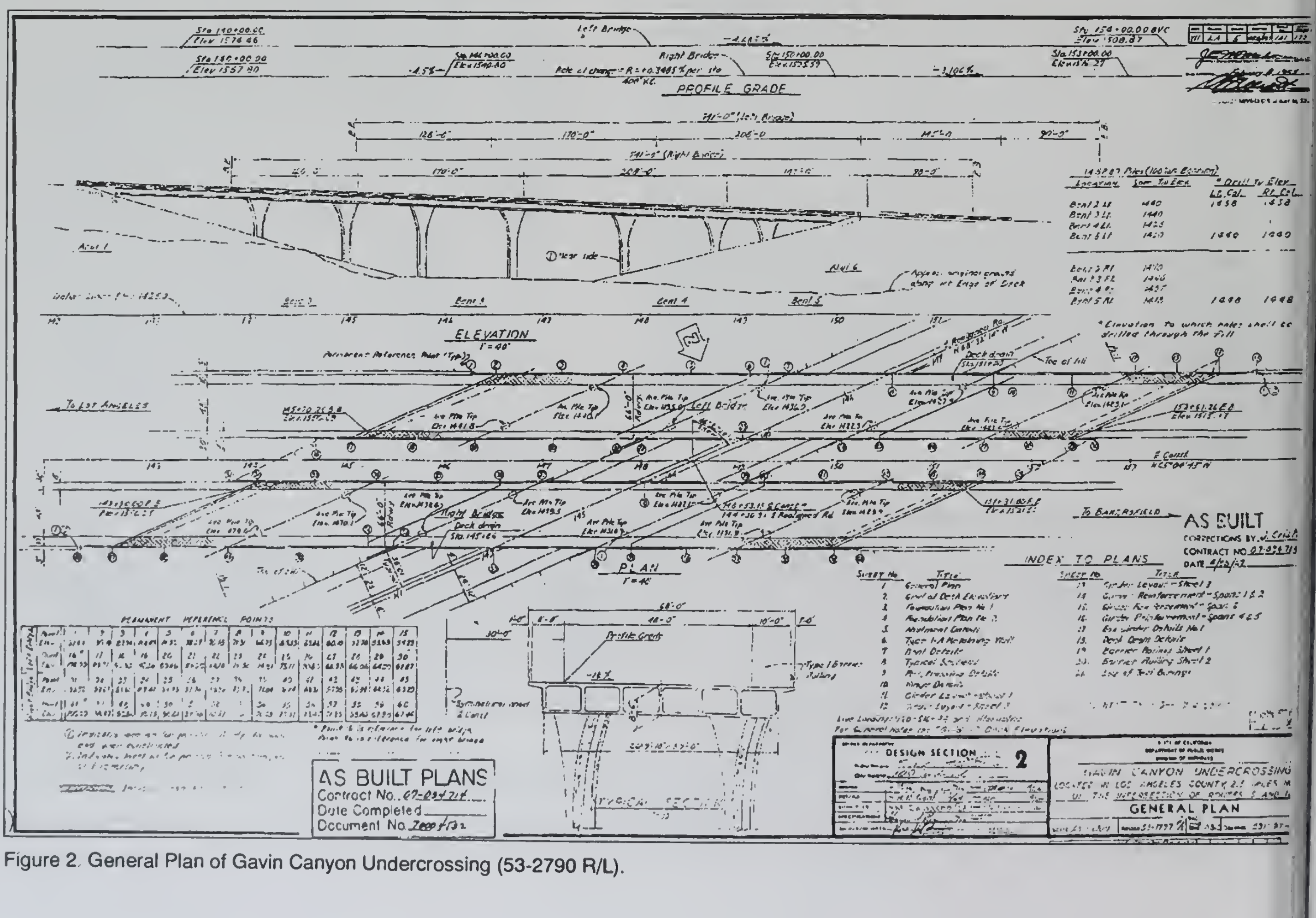


Figure 2. General Plan of Gavin Canyon Undercrossing (53-2790 R/L).

Damage

As can be seen from Photo 1, the cantilever spans came off of the hinge supports during the earthquake, dropping part of the superstructure onto the roadway below. There was also some minor damage at the abutments. There was no damage to the center span or to the columns.

Analysis of Damage

The major damage to these bridges during the earthquake was due in large part to a failure of the cable restrainers to limit superstructure movement. This may have been due to a tendency of highly skewed bridges to rotate out of their hinge supports which was not considered in the restrainer design. Or it may have been the result of an early restrainer design that did not prevent the superstructure from moving the 8 inches off an inadequate hinge seat. The result was that the cantilever spans moved off the hinge seats breaking off the acute corners of the cantilever spans. It may be that this three-frame design with cantilever spans supported on hinges is not a good choice for highly seismic zones. The end spans were much stiffer than the center span, which accentuated the problem. The replacement structure has no hinges.

14/5 INTERCHANGE

This interchange was under construction during the 1971 San Fernando earthquake and several bridges were damaged and replaced. The bridges are mostly long, curving connector structures (Figure 3, Photo 2). The site is surrounded by mountains and the bridges are supported by sandstone with some structural fill at the approaches. This site is about 8 miles from the epicenter of the Northridge earthquake and the peak ground acceleration is fairly close to that experienced at Gavin Canyon 2 miles to the north. The Lamont-Doherty Earth Observatory took readings of aftershocks at this site and noted a large variation in ground motion. Whether this variation contributed to structural damage has yet to be determined.

Structure

This structure connects southbound Route 14 to southbound I-5 (Figure 3). It was a 1,582 foot-long curved bridge with 10 spans and 5 frames. All of the columns had been built and the end frames had stem and soffits on falsework when the 1971 San Fernando earthquake occurred. Damage from that earthquake was caused by settlement of falsework and soffit cracks around Pier #3. This damage was considered minor and construction was completed in 1974 with a change order for the addition of restrainers at the four 14-inch hinges. The bridge had alternating prestressed and reinforced concrete box girder frames on single column bents. Figure 3 gives an indication of the varying column heights and

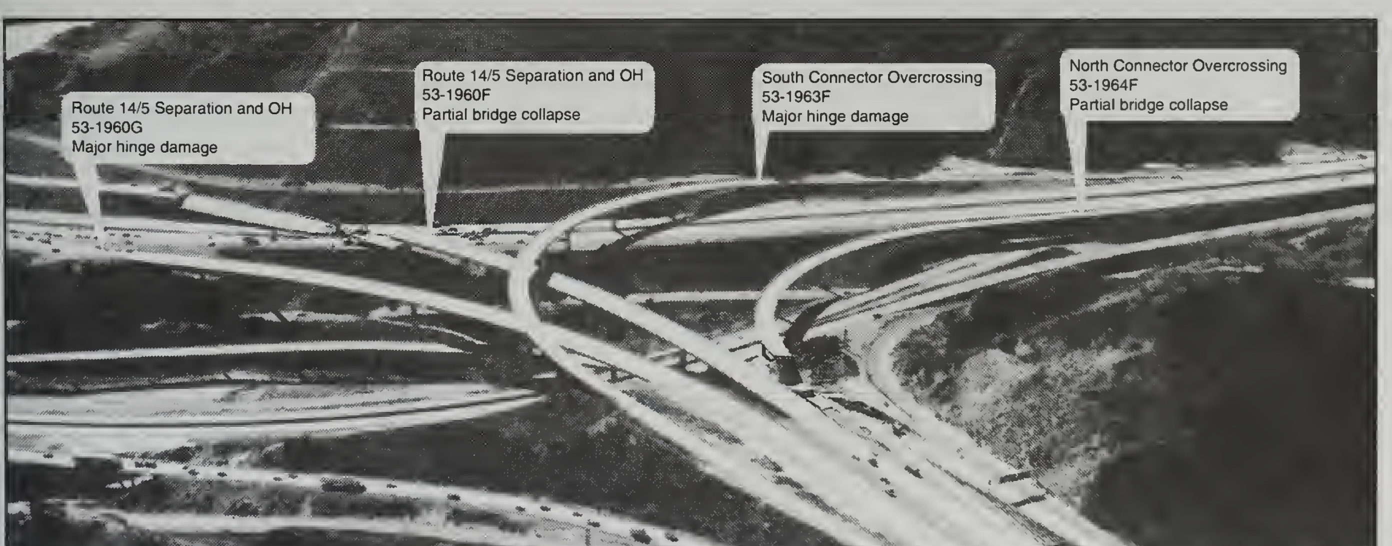


Photo 2. Bridge damage at Location 2 - Route 14/5 Interchange Overhead (53-1960F).

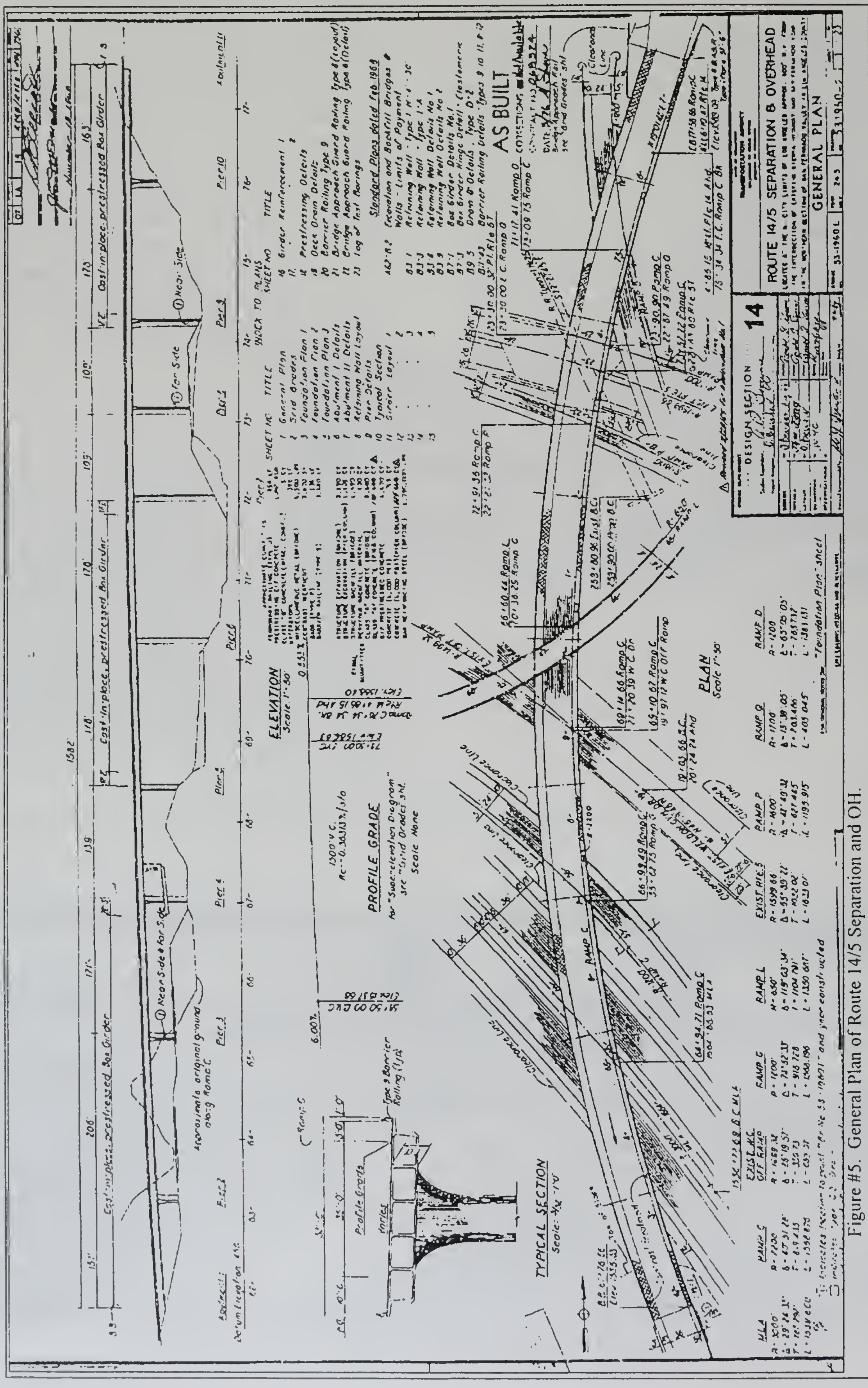


Figure #5. General Plan of Route 14/5 Separation and OH.

Figure 3. General Plan of Route 14/5 Separation and Overhead (53-1960F).

Photo 3. Damage at Pier #3, Route 14/5 Separation and Overhead.

span lengths. The columns had 12 foot by 4 foot or 12 foot by 6 foot octagonal sections with flares at the top and pile shaft foundations. The abutments were seat type on spread footings and with elastomeric pads to support the superstructure.

Damage

This bridge is 8.2 miles from the epicenter of the Northridge earthquake. A peak ground acceleration of at least 0.7 g was estimated for this site. The first frame of the bridge collapsed and fell to the east. The only damage to Abutment #1 was the failure of the right shear key as the superstructure moved to the right. At Pier #2 the longitudinal column reinforcement remained attached to the bent cap but the column concrete was in rubble. Pier #3 remained standing but the superstructure on both sides of Pier #3 and the bent cap lay on the ground (Photo 3). At Hinge #1, all the restrainers and equalizing bolts had failed in tension and there were concrete spalls indicating banging of the hinge.

Analysis of Damage

Figure 3 shows that Frame #1 was short and stiff whereas Frame #2 was tall and flexible. In particular, Pier #2 was very short and had a large flare that further increased its stiffness. This extremely stiff column was unable to displace elastically as much as the rest of the bridge and failed. The ground around the columns of Frame #2 showed that this frame moved to the left (outwardly) about 6 inches during the earthquake. This apparently unseated stiff Frame #1. Thus, the superstructure at Pier #2 and at Hinge #1 fell leaving Pier #3 standing (Photo 3). This was because there was no continuous reinforcement through the bent cap and perhaps because of the previously formed soffit cracks during the San Fernando earthquake.

North Connector Overcrossing

Structure

This was a 10 span, highly curved bridge on single column bents ranging from 25 to 75 feet in height. The bridge was 1,532 feet long with alternating prestressed and reinforced concrete superstructure frames. Frame #1 was a drop in span supported by a seat type abutment (Figure 4, Photo 4). Frame #2 was a 3 pier frame supporting the other end of the drop in span. Frame #3 was 2 long spans with a single column. Frame #4 was similar to Frame #2 with 3 columns and short, cantilevered end spans. Frame #5 was supported by 2 piers and an end diaphragm type abutment. There are hinges in spans 1, 4, 5, and 8. The hinges seats were 14 inches. All the columns were 8 feet by 4 feet octagonal sections with flared tops and a mix of pile and spread footing foundations. The bridge design began in 1968, was modified after the 1971 San Fernando earthquake, and was constructed in 1975.

Damage

The first 2 spans along with Pier #2 fell during the earthquake. There was also a great deal of movement at Hinge #2. There was no damage at Pier #3.

Analysis of Damage

Pier #1 was too short and stiff to handle the bridge's displacement and failed, dropping the first 2 spans.

Perhaps the end diaphragm abutment at the other end of the bridge, along with a frame with more piers restrained displacement, protecting short, stiff Pier #10 from a similar fate. Also the restrainers at Hinge #1 do not appear to have restrained the movement at this end of the bridge.

Photo 4. Earthquake damage at Abutment #1 to the North Connector Overcrossing.

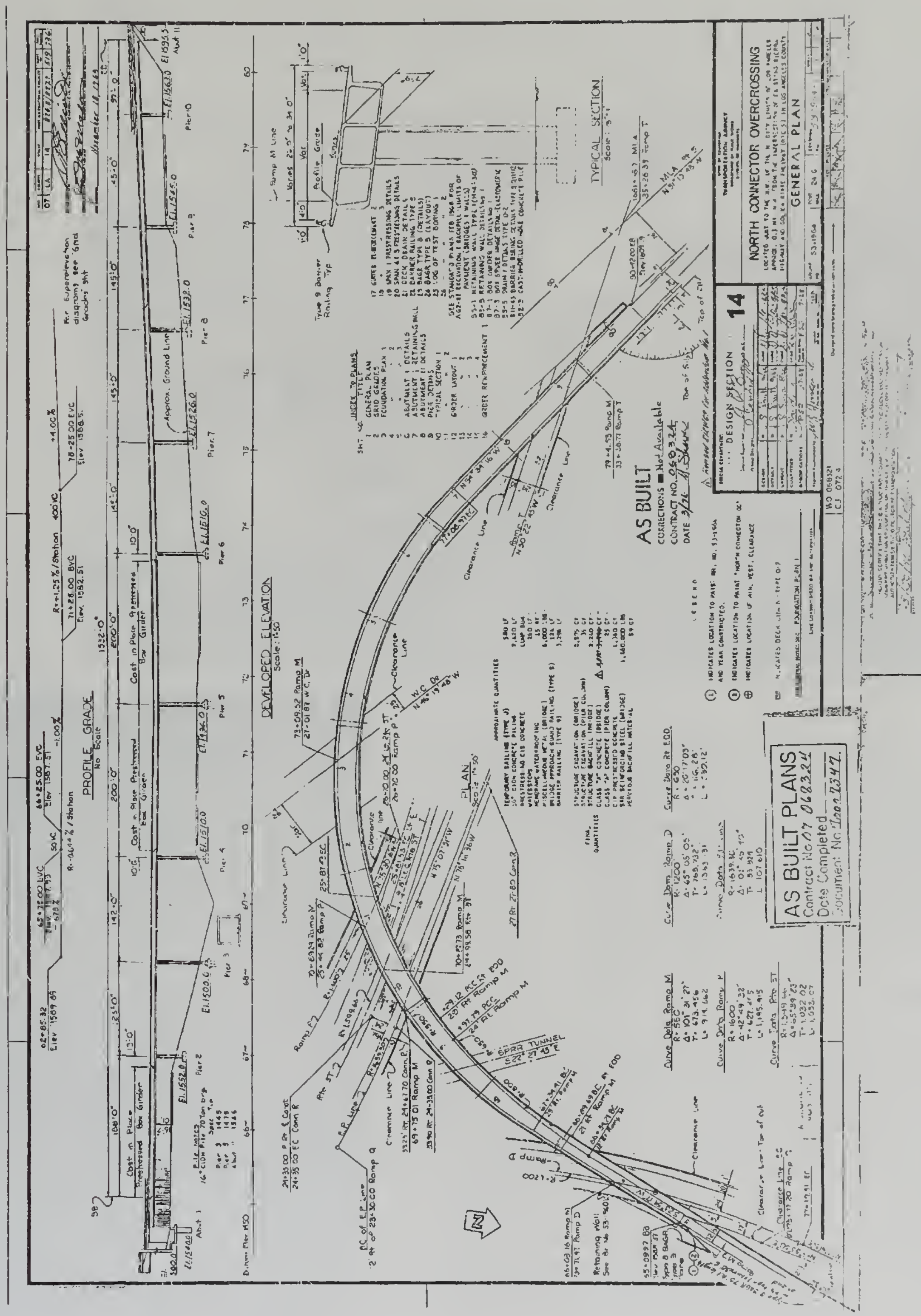


Figure 4. General plan of North Connector Overcrossing (53-1964F).

ROUTE 118 WEST OF ROUTE 405

This is the closest site to the Northridge earthquake that experienced severe bridge damage (Figure 5, Photo 5). It is about 5 miles northeast of the epicenter of the earthquake. Every bridge along Route 118 for several miles west of I-405 suffered some damage from the earthquake. This damage ranged from approach settlements to superstructure collapse. Due to the extent of damage, a peak horizontal ground acceleration of at least 0.5 g is estimated for this site. This is somewhat higher than what was recorded on instruments near this site.

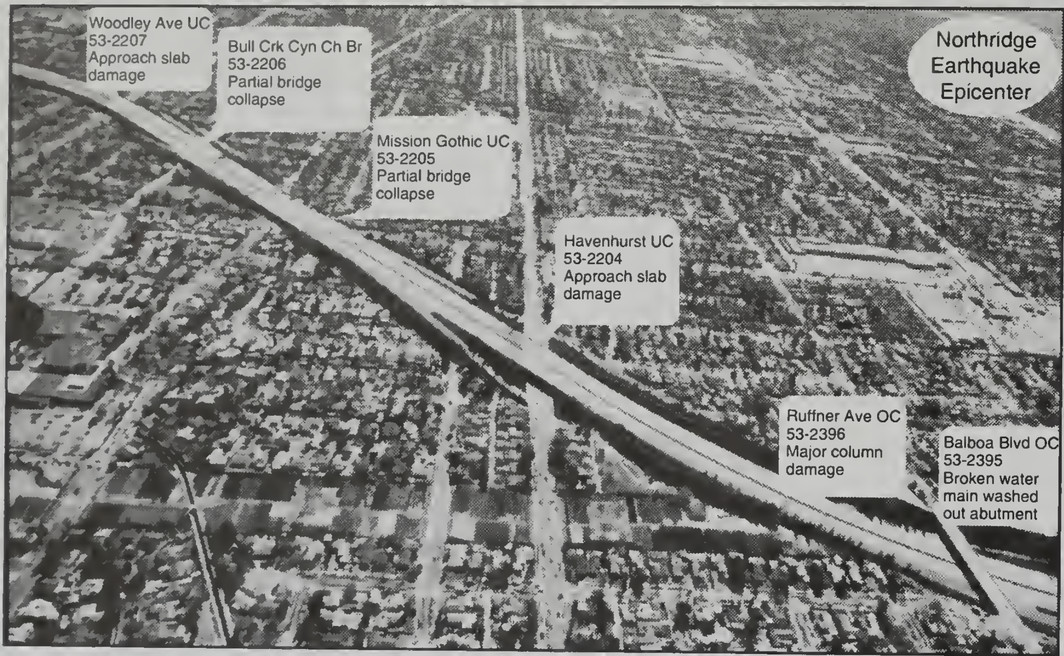


Photo 5. Bridge damage at Route 118 west of Route 405.

The ground consists of at least 90 feet of compact silts, sands, and gravels. All of the bridges at this location were built in 1976 which means that some of the new ideas about seismic design were incorporated into their designs. The bridges are all medium length prestressed concrete box girder structures.

Mission Gothic Undercrossing

Structure

These two bridges had a rather unusual geometry with opposite skews at the two ends. The left bridge had three spans and was 506 feet in length (Photo 6). The right bridge has four spans and was 566 feet in length. The cast in place prestressed box girder superstructures were supported by two column bents with prestressed bent caps. The columns had a 6 foot octagonal section with flares on top and pins at the footings. The columns had excellent transverse reinforcement of #5 spirals each at 3 1/2 feet up to the flare. All the abutments had 4-foot seats and supported the superstructure on elastomeric pads. All the foundations were supported by 16-inch cast in drill hole (CIDH) piles. The bridges were designed in 1973 and built in 1976.

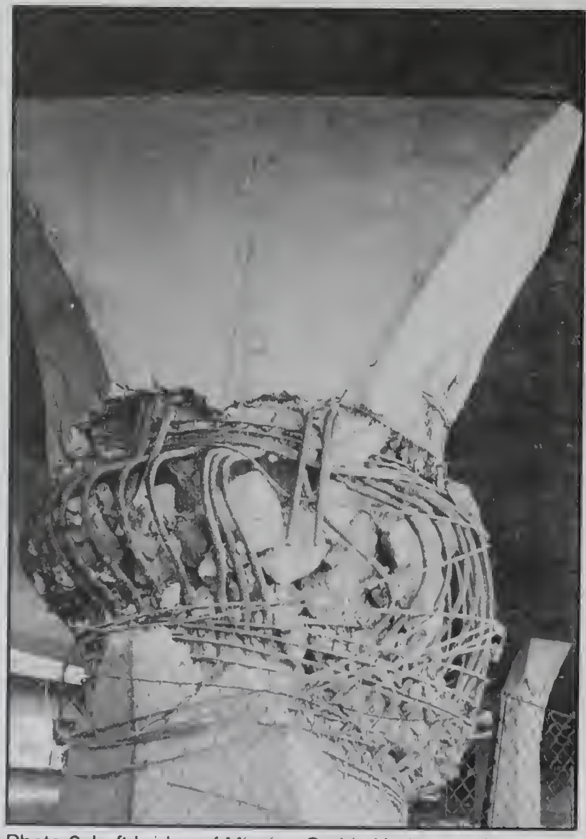


Photo 6. Left bridge of Mission Gothic Undercrossing.

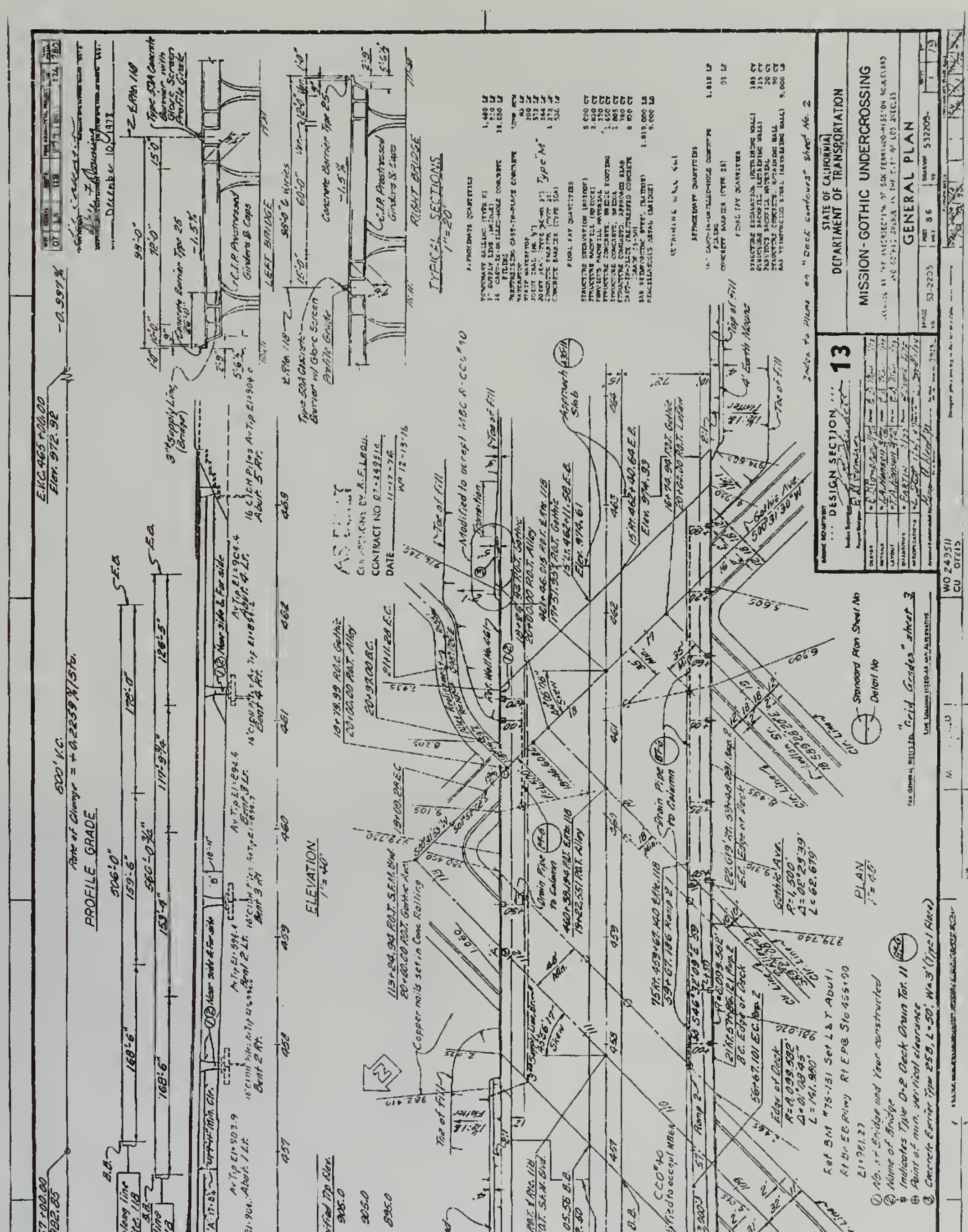


Figure 5. General Plan of Mission Gothic Undercrossing (53-2205).

Damage

Both bridges suffered serious damage during the earthquake. The right bridge had a collapse of spans 3 and 4. The columns at Bents #3 and #4 broke off below the flares, dropping the superstructure and unseating it at Abutment #4. The superstructure remained seated at Abutment #1 although there were 13 inches of transverse movement. At Bent #2 the left column also failed below the flare; however, the right column broke the bottom pin instead. The left bridge did not collapse; however, most of the columns failed below the flare. There were 2 inches of transverse movement at Abutment #1 and over 10 inches at Abutment #4.

Analysis of Damage

There were two factors that controlled the dynamic behavior of these bridges. The first is the unusual geometry that allowed movement only to the south during the earthquake. This directional bias may have forced some columns to move in their stiff direction, where they could not displace very far elastically. The other factor is the large flares that effectively reduced the elastic length of the columns, causing a much greater plastic shear to develop (Vp=Mp/L). Thus, the largest plastic shear failed the weakest column section just below the flares and in one case at the column pin. Other factors that influenced the bridge damage were the wide spacing between columns, forcing fewer columns to carry more of the seismic load, and a larger dead load. The progression of events after Bent #4 of the right bridge and Bent #3 of the left bridge is harder to determine. Most probably the increased displacements that occurred after these bents failed, broke the rest of the columns, and dropped the right superstructure off of its east abutment.

Bull Creek Canyon Channel Bridge

Structure

Bull Creek has two highly skewed bridges connected with a longitudinal joint on the centerline of Route 118 (Figure 6). They were cast in place, prestressed box girder bridges. Both were three-span structures with multicolumn bents and diaphragm type abutments on foundation seats. The foundations had 16-inch diameter CIDH piles. The superstructure widened from a minimum width of 200 feet and had a large skew. The columns had a 4-foot octagonal section without flares. At Bent #3, the columns were cast into a concrete channel. Bent #2 columns had an octagonal section for their entire length. The three spans were 90 feet, 101 feet, and 65 feet, respectively.

Damage

At Bent #2, the right bridge had major column damage near the top of two of the five columns. This damage included breaking of the spiral reinforcement, buckling of the steel longitudinal column, and crushing of the concrete column into rubble. This occurred at one diameter below the soffit where the confinement steel changed from a 3-inch to 12-inch spacing. At Bent #3, both bridges had major column damage right above the concrete culvert (Photo 7). The only other damage observed was some soil heaving at Abutment #4 of the right bridge, and some minor concrete cracks at the abutment shear keys and on the right bridge soffit at Bent #3. The bridges rotated clockwise during the earthquake.

Analysis of Damage

Major damage was caused by Bent #3 being monolithically cast with the channel wall. This made the columns much shorter and stiffer. The result was that the bent was too stiff to displace with the rest of the structure. It immediately failed causing secondary damage to Bent #2 of the right bridge and other minor damage. It should also be noted that no bridge in this area escaped damage during the Northridge earthquake.

Photo 7. Earthquake damage at Bent #3, Bull Creek Canyon Channel Bridge.

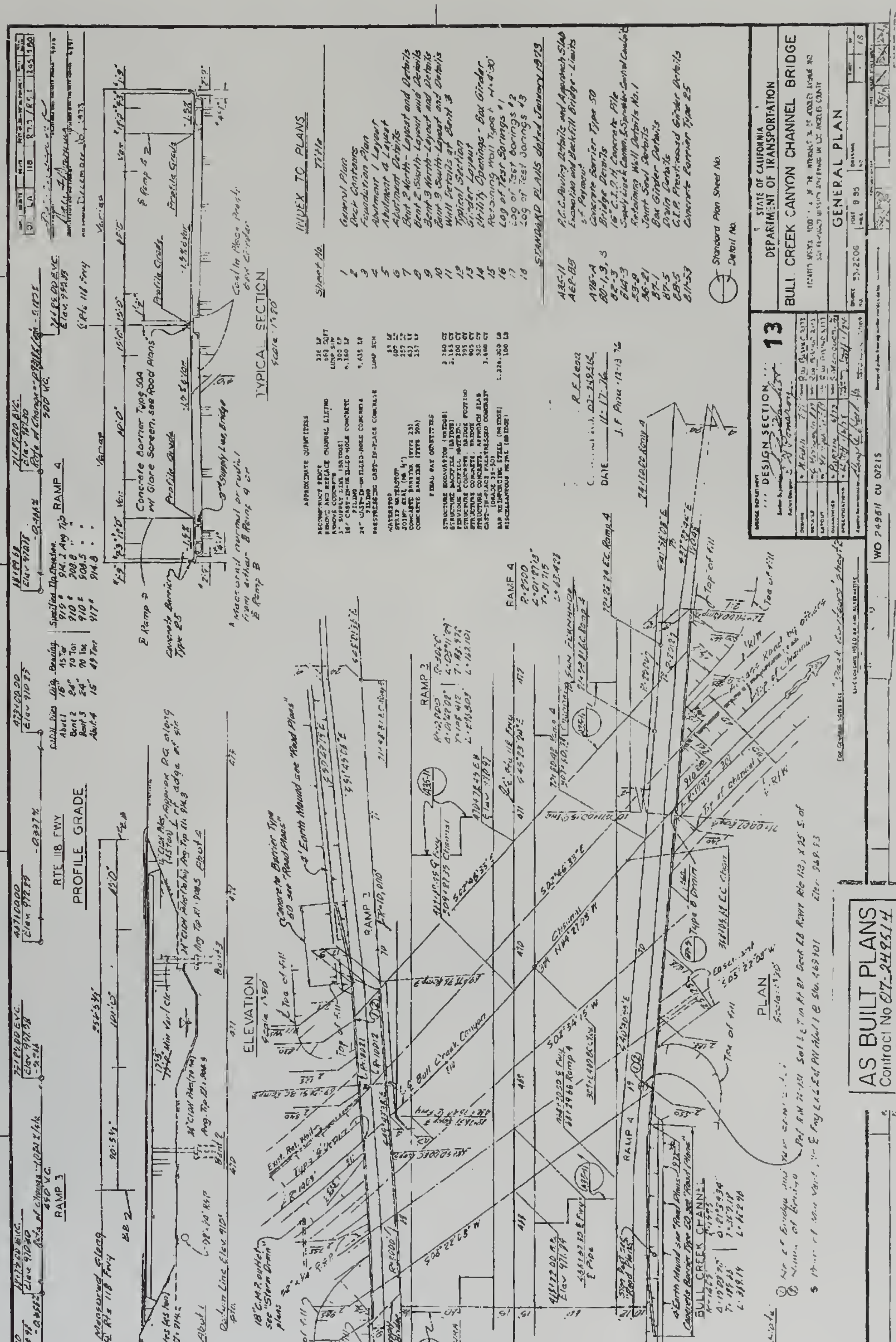


Figure 6. General plan for Bull Creek Canyon Channel Bridge (53-2206).

Photo 8. Santa Monica Freeway south of downtown Los Angeles.

SANTA MONICA FREEWAY SOUTH OF DOWNTOWN LOS ANGELES

This location is 16 miles southeast of the epicenter of the Northridge earthquake (Photo 8). The Santa Monica Mountains and a deep basin filled with alluvial deposits lies between the bridge and Los Angeles. This site is on the southern edge of the basin, in an old stream basin softer than the surrounding area. Peak accelerations of less than 0.3 g were recorded 2 miles away. However, the geology and damage suggest that higher accelerations occurred at this site. The damaged bridges were part of an east-west freeway built in the early 1960s.

La Cienega-Venice Undercrossing

Structure

These were two 9-span bridges connected with a longitudinal joint. The left bridge had a constant width of 70 feet and the right bridge widened to carry traffic onto an adjacent ramp (Photo 9). The bridges were supported by substructures on skews ranging from 5 degrees at Abutment #1 to 41 degrees at Abutment #10. The superstructures were 6 feet-3 inches deep, cast in place, reinforced concrete boxes composed of three frames and connected by 6-inch hinge seats. The bridges are 870 feet with spans of 51,116, 93, 111, 112, 105, 116, 115, and 51 feet. The end spans were slab and girders with crib walls to form closed bins at the abutments and pier walls.

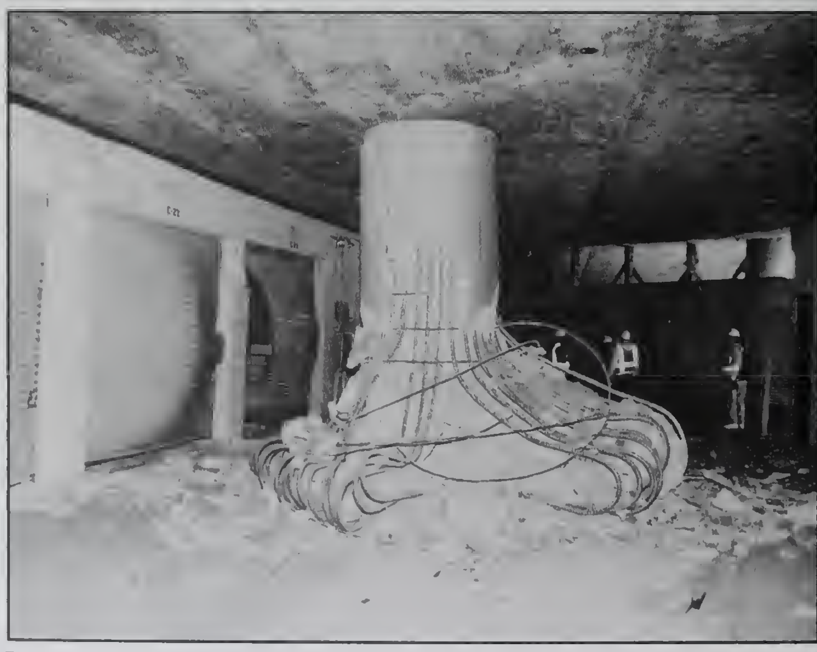


Photo 9. Damage to La Cienega-Venice Undercrossing

Bents #3 through #8 had 3 or 4 (6 to 8 for both bridges) four-foot diameter prismatic columns with #11 longitudinal reinforcement and #4 lapped hoops at 12 inches. Bent #4 had columns that were pinned at the bottom with a 6-inch ring of expansion joint material. There was a decreasing superelevation that caused a significant variation in the column heights of Bents #3 and #4. Piers #2 and #9 were concrete pier walls with lapped vertical reinforcement above the footing. All of the footings were inadequately reinforced and were supported on piles.

The soil profile shows at least 70 feet of sandy soil. The bridges were built in 1964 and seismically retrofitted in 1978. The retrofit was the installation of $1^1/_4$-inch diameter, high strength restrainer rods at the hinges.

Damage

Most of the columns were severely damaged by the earthquake. Both superstructures dropped onto masonry storage buildings that were under the bridges. All of the columns at Bent #7 on the left bridge failed, two at the top and the middle one at the bottom. These columns were designed to be fixed at the bottom. Span #6 of the left bridge fell off of the hinge seat. The restrainers at that hinge sheared or were pulled through the concrete diaphragm. A separate but adjacent collector ramp structure also suffered some column damage. The column foundations were exposed after the earthquake and were found to be in excellent shape.

Analysis of Damage

These bridges collapsed due to column failures. Specifically, #4 hoops at 12 inches failed before a plastic hinge could form and because they could not resist the large shear forces during the earthquake. In every column, failure began with rupturing of the #4 hoops, usually near the top or bottom plastic hinge zones. This is not surprising considering when these bridges were built. A seismic retrofit project for these bridges was about to begin at the time of the earthquake.

The bridges were 16 miles from the epicenter of the Northridge earthquake. SMIP Station #24157 recorded 10 seconds of significant shaking with a peak east-west acceleration of 0.25 g and a peak north-south acceleration of 0.17 g. This station was 2 miles to the southeast of the bridge sitting on 3 feet of soil over rock. SMIP Station #24389 recorded 10 seconds of strong shaking with a peak east-west acceleration of 0.27 g and a peak north-south acceleration of 0.24 g. This station was located 4 miles to the northwest on terrace deposits. It was surprising to see the extent of damage to these structures at those accelerations. Perhaps being located on a soft basin amplified the earthquake motions.

Fairfax-Washington Undercrossing

Structure

The Fairfax-Washington undercrossing consisted of two cast in place, reinforced concrete, box girder bridges. They were 577 feet long. Each had two frames. The right bridge had seven spans and the left bridge had eight spans. Both bridges had varying widths with the right bridge varying from 72 to 74 feet and the left bridge varying from 72 to 110 feet. The bridges were supported by skewed supports varying from 5 degrees at Abutment #1 to 45 degrees at Abutment #8. The hinge seat width was only 6 inches. These bridges were very similar to La Cienega-Venice Undercrossing. The pier walls were adjacent to the abutments (with pinned bases on cast in drill hole pile foundations). The other bents had three to four 4-foot diameter columns (some pinned at the base and others with fixed bases all on cast in drill hole pile foundations) with #11 bars longitudinally and #4 bars at 12 inches transversely. The soil is similar to La Cienega with an excess of 70 feet of dense sand. The superstructure rested on 6-inch high bearing assemblies at the abutments. The abutments had spread footings. The bridges were built in 1964 and retrofitted with five and seven cable restrainer assemblies in 1974.

Damage

Damage to these bridges, although severe, was somewhat less than at the nearby La Cienega -Venice Undercrossing. The tops of all the columns in Bent #3 for both bridges had major damage (Figure 8, Photo 10). This caused the superstructure to sag about 10 feet at Bent #3 and lift about 5 feet above the rocker assembly at Abutment #1. The bottoms of the columns at Bent #3 were designed as fixed with lapped reinforcement above the footing. There was also some cracking of concrete on the columns at Bent #4. The restrainers did a good job of keeping the superstructures from falling off of the hinge seat.

Analysis of Damage

These columns had shear failure, probably after some plastic hinging occurred at the top of the columns. This hypothesis is based on the fact that there was no damage at the pinned bottoms of the columns which otherwise would have been more vulnerable to shear. This damage was similar to the nearby La Cienega - Venice Undercrossing (Figure 7), and it occurred for similar reasons. The columns at Bent #3 did not have sufficient confinement reinforcement. What is surprising is that such catastrophic damage could occur so far from the epicenter and at such a low acceleration. The footings and piles at Bent #3 were exposed and found to be in excellent condition.

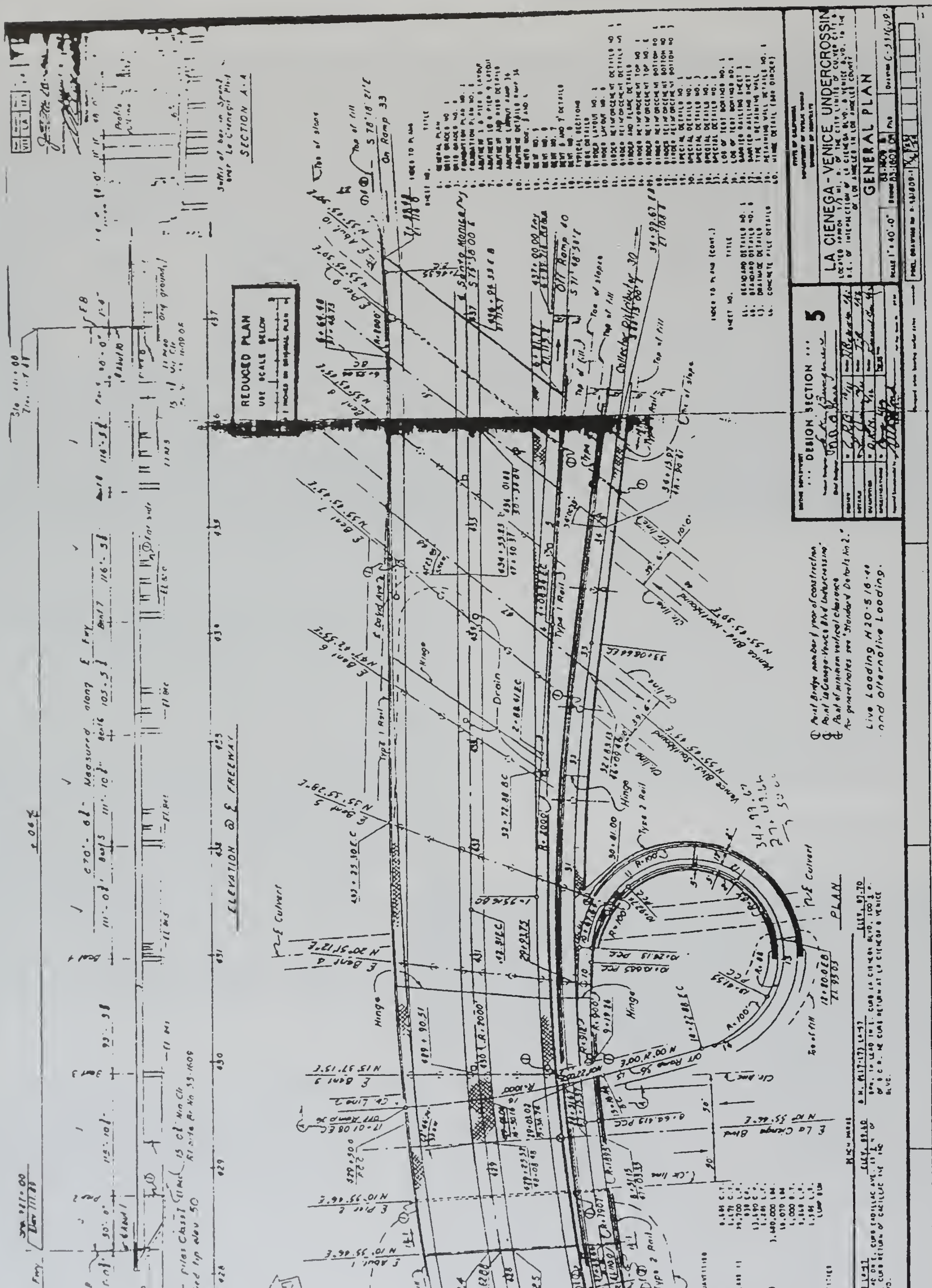


Figure 7, General Plan for La Cienega-Venice Undercrossing. (53-1609).

Photo 10. Damage to Fairfax-Washington Undercrossing.

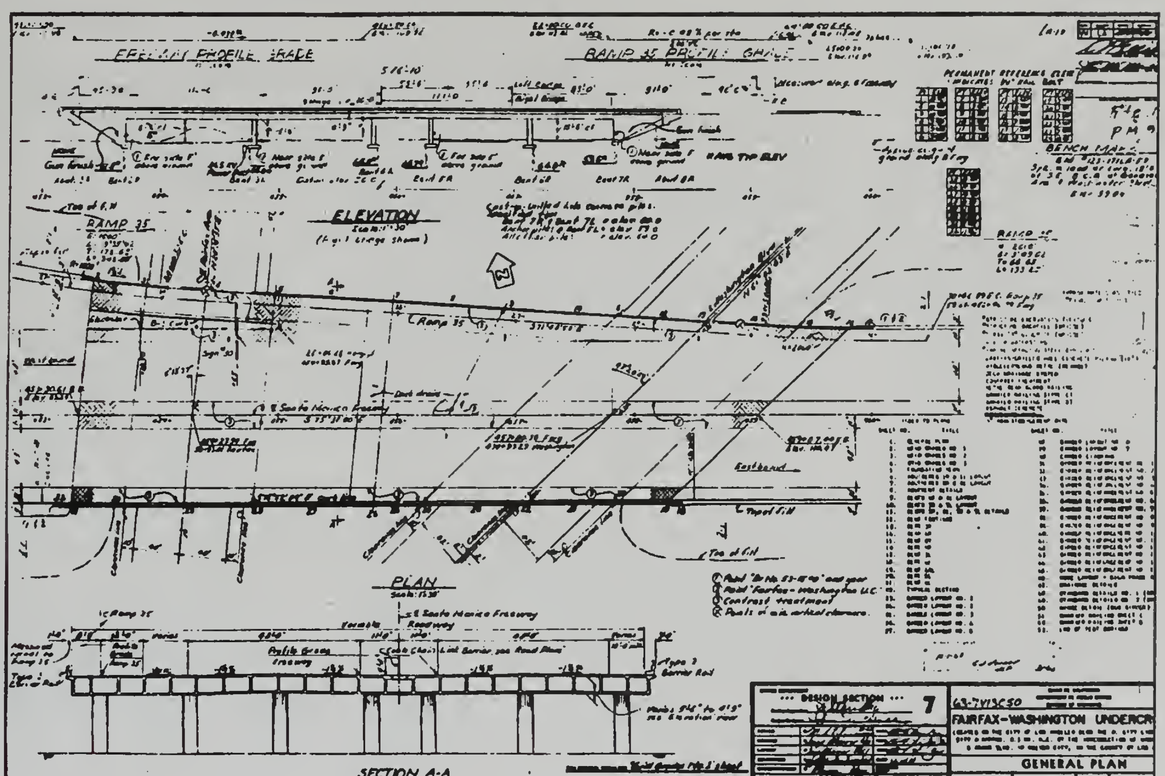


Figure 8. General Plan of Fairfax-Washington Undercrossing (53-1580).

OTHER BRIDGE DAMAGE

Besides the catastrophic bridge damage listed above, a great deal of other damage occurred, much of it minor and some of it more serious. Most of the damage consisted of cracks and spalls associated with superstructures banging against abutments and piers. More serious damage resulted from restrainers punching through hinge diaphragms. In many instances shoring was provided under hinges until repairs were made. Table 2 gives a complete description of all state highway bridge damage from the Northridge earthquake.

Table 2. Highway bridge damage from the Northridge earthquake.

Bridge #	Rte	Post mile	Bridge Name	Description of Bridge Damage
53-0498	1	36.89	BEACH PUC	Minor damage. Spalling at joints. PUC heaved inward causing longitudinal crack in #1 S'bnd lane. Cracking evident in other lanes.
53-0068	1	39.62	CASTELMARE POC	Slight spalling @ east abutment seal.
53-2602	1	36.25	MONTANA AV POC	HInge seperation - approx. 2". No recommendation. Supported on bottom also. No damage per Makoto Ogata on 3/9/94.
53-1580	10	R009.31	FAIRFAX WASH U	One span Collapsed abutment to hinge.
53-1603	10	R004.24	CENTLA-PICO UC	Top of columns have spalled. Spalls @ top of col, circumferential cracks @ top of col along Centinela Blvd. 0"Lx8"Wx2"D PCC spall w/ rebars exposed in N. rail. 3" settlement in approach slab over W. lane @ Cintinela Ave. off-ramp
53-1586	10	R010.43	LA BREA AVE UC	Spalls at R & L sides of B2 at the top corners of the curtain wall.
53-1599	10	R003.34	CLOVERFIELD OC	N.E.shear key, crack: bearing restrainer popped out with spall on wall; N. abutment has minor shear key spalling; N. abutment PN has 2' - 8"-3" spall; NW corner barrier separated. Raised Median @ N. abut. cracked. Top of all columns (4)
53-1609S	10	R008.83	LA CNG-VEN SEP	Column has formed plastic hinge @ B3. Structure standing but unsafe. Need to be Shored.
53-1609	10	R008.83	LA CNG-VEN SEP	Collapsed span hinge to adjacent span. Most of columns of mainline struct. buckled. Some damage on ramp col.
53-1572	10	R011.03	WEST BLVD OC	Hairline cracks at tops of columns. Slope paving cracked.
53-1301	10	14.23	SANTA MONICA VI	Minor Spalls at top of cols near I- 110(PM 14.85) Primarly drop caps are damaged. Possibble internal hinge damage: @ WB 10/NB 110; @ Los Angeles ST. Only substructure & W/B deck inspected WORK IS NOW AT SANTA FE AVE.
53-1637F	10	R005.65	SE CONNECTR OC	Cracks at exterior girders, bent 7. Unknown internal damage.Crack @ hammerhead cap expansion joint. Damage to diaphragm (hinge) is excessive.Cracks at exterior girders and restrainers and diaphragm damage at Bent 7.
53-1485F	10	R009.22	CADILLAC RP SP	Approach settlement. Crack in slope paving; Abut 1 approach settled 1/2"
53-1557	10	R007.92	ROBERTSON-N UC	Damage luminare (Maint. contacted); lt wingwall at eb cracked; broken keeper plate bolts at brg. Previously patched spall in EB gore area has popped off.
53-1288	10	31.72	BESS AVE POC	Minor damage to picket rails, some cracking of superstructure over route 10
53-1582	10	R009.74	HAUSER BLVD UC	Concrete spalls at Bent 3 curtain walls and wingwalls.
53-1587	10	R10.72	HARCOURT AVE UC	Minor concrete crack at Bent 3 curtain wall. No work required.
53-1570	10	R011.70	TENTH AVE OC	Minor horiz. concrete cracks at the top of all columns.
53-1571	10	R11.39	CRENSHAW BLVD. OC	Hairline Horiz. cracks @ top of all columns. Shear wall crack at north abutment.
53-1590	10	R12.10	FOURTH AVE POC	Minor concrete spalling of the external bolsters at both abuts.
53-1615	10	R006.31	NATIONAL BL OC	Rocker & keeper plate damage @ abuts, cracks in curtain wall, spalls at top of col. PECIT (1/18/94); all keeper plates failed.
53-1333F	10	18.41	ECHANDIA OH	Abut. Brg keeper plates sheared off. Barrier rail spall Rt rail @ abut. 1
53-1459G	10	21.33	RAMONA BLVD UC	Hairline cracks @ Bent 2, top of column
53-2055K	10	20.95	CAMPUS RD RAMP	Minor cracking in columns at Bent 2.
53-1856	10	19.98	CITY TERRC POC	Hairline cracks near hinge 2
53-1634	10	R005.99	COVENTRY PL UC	Curtain wall damage.
53-1627G	10	R005.28	NORTHW CONN OC	2" offset of span at Bents 3 and 16; 1" spall at B4 and B5 col/soffit interface. Damaged rail tubes. Bent 3, Cells 1 & 4 hinge restrainer damage.
53-1584	10	R010.12	REDONDO BLD UC	Minor Damage. E/B Approach Lane #1: 2"' Settlement. 2" Gap in Pier Walls. Sidewalk Buldged at Corners.
53-1553S	10	R007.08	MANNING A R OC	Cracks at east abut diaphragm. Spall at east abut deck joint.
53-1579	10	R009.12	BALLONA CREEK	Minor top of column spalls. Crack in wingwall. Retaining wall at A1 has moved out 5". Approaches settled 4" @ each end, there is plenty of evidence of structure movement.
53-1596	10	R002.61	14TH STREET OC	Bearing out of position at abutments.
53-1597	10	R002.84	17TH STREET OC	Minor spall and hairline cracks at top of all columns.
53-2540L	10	C021.07	WBD BUSWAY OC	Crack top of column in outrigger Bent #5.Noticed 1 cm vertical crack on top of the right column over outrigger Bent #5. At same bent cap outrigger column connection previous patches due to earthquake has fallen and rebar is exposed.
53-1598	10	R003.07	20TH STREET OC	30' LongTransverse AC Crack over N'ly Abut in Bridge Approach Lanes #1 & #2.
53-1616	10	R006.40	OVERLAND AV OC	W Side S Abut Seat Cracks & Spalling. Top of Col Cracks.
53-1671K	10	R009.13	BALLONA CREEK	Approach Slab Settled 5". Horiz Crack Below Box Gdr in A1 Diaphragm.
53-1603	10	R004.24	CENTLA-PICO UC	Top of columns have spalled. Spalls @ top of col, circumferential cracks @ top of col along centinela Blvd. 0"Lx8"Wx2"D PCC spall w/ rebars exposed in N. rail. 3" settlement in approach slab over W. lane @ cintinela Ave. off-ramp
53-1442	101	31.05	LAS VIRGENE OC	Superstructure dropped 3"-6".?? Abut. 1&5 were thrust upward above sidewalks & A.C. approaches. Possible pile damage.
52-0266	101	7.89	WENDY DRIVE OC	Exterior girder fillet spalled.
53-1339F	101	11.63	134/101,170SEP	Top of column spalling with some exposed rebar. Shear key failure. Numerous keeper plates broken.
53-0731	101	6.15	WILTON PLACE O	Shear cracks and spalls at curtain wall A1. Keeper plate bolts sheared off on one side. Spall at A3.
53-1336R	101	11.75	101/134,170 SP	Shear Key Failure. Bearing restraint caused spall on abutments. Major column failure of Bent 5. Abut 9 rocker bearing damage. Minor spalls both sides of long span @ span 5 and span 7 hinges. Minor spalls @ Bent 6. Buckled bar @ col 4 of Be
53-1102R	101	16.94	SEPULVEDA BL U	No Damage. Soundwall down (300'), otherwise no damage to bridge structure.
53-1095	101	25.88	SHOUP AVE UC	No Damage. Soundwall damage (300' out of alignment)
53-0676	101	5.81	WESTERN AVE OC	SE End of Br: Buckled AC & Separation of Steel Girder at Abut. No damage per Makoto Ogata on 3/9/94.
53-0732K	101	6.41	VAN NESS A RP	South abut shear wall badly cracked and spalled. North abut shear wall cracked. Spall at barrier rail at N abut.
53-1337	101	13.27	TUJUNGA WASH	Out of plane hanger plate bending. Minor to moderate cross frames buckling at several locations. Abut joint wingwall cracks. Minor barrier rail damage.
53-1371	101	15.38	LOS ANGELES R	Top of column spalling. Keeper plate bolts have sheared off @ Abut 6 with loss of bearing. East abut not inspected. Curtain wall damage. WW (Bin Type Abut) Damaged.

Table 2. continued

Bridge #	Rte	Post mile	Bridge Name	Description of Bridge Damage
53-1064	101	25.34	ROUTE 101/27 SEP	Minor Conc Spalls & Cracks: A1 S Widen Conc Header, B2 S Widen Cols #1 & 2 & @ Ctr Widen, A3 Sidewalk from Gdr #6 N to End of Bridge.
53-1224	101	10.86	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-2405R	105	R7.39	RTE 105/110 SEP	Bearing showed 4" movement. Abut face spall.
53-2655	105	R3.47	IMPERIAL HWY OC	Minor Spalls at the E'ly Two Shear Keys of the S'ly Abut.
53-2428	105	R14.95	MERKEL AVE OC	Minor Concrete WW Spall @ N'Wly Corner.
53-2425	105	R14.65	PARAMOUNT BLVD OC	Minor Cocrete WW Spall @ SW'ly Corner.
53-2565S	105	R15.76	LAKEWOOD BL OC	Minor conc spalls in abut faces at NE'ly & SW'ly corners.
53-2572	105	R16.39	ARDIS AVE OC	Minor conc spall in abut face at W'ly side of N'ly abut.
53-2680	105	R7.68	NE TRANSIT CONN OC	Minor spalls at hinge #8.
53-0956	110	10.49	GARDENA BV UC	Minor Exterior Rail Spalls at Jts.
53-0960	110	9.07	190TH ST UC	Minor Spall at N Abut Wall.
53-2465	118	R007.05	ENCINO AVE OC	4" settlement on approach. Curtain wall damage. Cracks ext. shear keys @ abut. 3 RT & LT side. Curtain wall connections damaged @ A1 (DBR). Soundwall Damage.
53-2395	118	R007.80	BALBOA BLVD OC	Minor spalls at top of column. Approach slab buckled. A1 & B2 damage is significant. Water mains washing out abut. Slope paving damage.
53-2396	118	R008.05	RUFFNER AVE OC	Column cracks.
53-2207	118	R009.04	WOODLEY AVE UC	Spalls at both abuts, seat damaged at SW abut, barrier rail damage at both abuts, median barrier damaged. Severe approach slab settlement
53-2204	118	R008.34	HAVENHURST UC	App slab buckled. West bound struct. appears to have rotated. Slope paving damaged.
53-2208	118	R009.33	GAYNOR AVE UC	Approach slab settlement; N. E. wingwall settled + - 1 FT. Wingwall and approach slab damage?. Failed sidewalk & heavily damaged slope paving.
53-2215	118	R010.83	FOX STREET UC	Minor approach slab settlement. A1-midwidth cracking-1/8" vertical rt. WW 4" transverse separation. A2 left WW 3" longitudinal separation, 1/8" midwidth crack in diaphragm, minor cracking-1" settlement in approach slabs
53-2209	118	R009.57	HASKELL AVE UC	Severe approach slab settlement
53-2213	118	R010.07	SEPULVEDA B UC	Bridge slab buckled. A1 & A3 vertical cracking in diaphragm, slope paving cracking and settlement. Hairline cracks in all col. 2" settlement at both approach slabs (DBR).
53-2464	118	R006.80	WHITE OAK A OC	Shear keys cracked. Interior shear keys @ a1 & A3 damaged. Both keys remain partially effective. Steel is exposed (DBR)
53-2513	118	R006.58	ZELZAH AVE OC	Cracked slope paving & minor spalling
53-2205	118	R008.63	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2206	118	R008.84	BULL CR CYN CH	Rt Str.partially collapsed, super not repairable. Lt Str. all columns failed. Super intact. Some columns poking through deck.
53-2095	118	R012.40	SAN FERN RD OH	Damage at abut 3; soffit spalled; cracked end diaphragm; column looks good
53-2103G	118	R013.89	PAXTON-FTHL UC	Minor spalling at hinge seats. Signs of movement @ hinge bad/torn joint seals , lamp of electrolier fell off.
53-2102G	118	R013.94	RTE118/210 SEP	Seal failure @ hinges, offset in hinges, spalls in soffit. Restrainer damage at span 5 (cell 1) and span 8 (cells 1,2,3 & 4). Minimal to moderate rotation of Abutment 11. Minor damage to exterior keys. Light standard bases are broken. Stan
53-2354S	118	R012.27	PAXTON ST UC	Minor abut spall, approach settlement
53-2210G	118	R009.70	CHATSWTH ST UC	Minor spalls at abut., vertical minor cracks down face of wingwalls
53-2324L	118	R011.42	RTE 118 5 SEP	Bridge rail cracking SW end of bridge. Some approach settling in shoulders.
53-2342L	118	R011.31	SHARP AVE UC	Minor Abutment Damage
53-2342R	118	R011.32	SHARP AVE UC	Abut. 2 cracking and spalling; joint seal damage; 3" approach slab settlement
53-2343G	118	R011.32	SHARP AVE UC	Cracks and spalls at Abutments; 1 " approach settlement
53-2357	118	R011.05	ARLETA AVE UC	A-1: lateral movement at wingwall; A-2 minor crack and 1" wingwall displacement; cracked slope paving
53-2212F	118	9.85	CENTER CONN OC	Extensive cracking at Abut. 7 ,1/4-1/2 inch (total 5), in pile cap. 2" & 1-1/2" transverse seperartion of backwall and wing wall at Abut. 1. Possible pile damage Bents 2-6. Hinge restrainer damage in Spans 2 & 5.
53-2214	118	R010.51	CHATSWORTH D U	A1: 4" lateral movement of right WW. 1/16" vertical crack in abut diaphragm @ midwidth. A2:3" long. & 2" lat. movement of left WW. 1/8" vertical crack at midwidth of diaphgram
52-0300	118	R029.56	YOSEMITE ST OC	Evidence of plastic hinging. Cracking at tops & bottoms of columns. 4" approach settlement. Approach settlement.
53-2499	118	R003.22	MASON AVE OC	Cracked slope paving. One small spall at A3 backwall. Approach settlement. Abutments have rotated, gap approx. 1 1/4 ".
53-2217H	118	R009.74	DEVONSHIRE UC	Minor abut. cracking. Minor soffit cracks. WW movement. Leaky joints
53-2182	118	R002.55	BROWNS CYN WA	Cracked Keys/Bearing Pads Delamination. Approx 4" Transverse Movement Crack at Abut Shear Keys. Sheared Bearing Pads.
53-2498	118	R003.13	RINALDI ST OC	Wingwalls separated from Abutment diaphragms. Slope paving cracked near diaphragm/poss.Pile damage.
53-2328G	118	R011.41	PACOIMA WASH	Abut 1 joint seal needs to be replaced. Sections of barrier at abut needs to be repaired. Spall on north/east wingwall need to be patched. Significant signs of movement. Repair cracks in shear key and abut. face.
53-2500	118	R003.86	WINNETKA AV OC	Approach Settlement
52-0334L	118	T19.19	PRINCETON AV UC	Concrete spall on face of Abut. 1.
53-2205	118	R008.63	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2502S	118	R004.60	BROWNS CYN WA	Cracked Keys/Bearing Pads Delamination. Approx 4" Transverse Movement Crack at Abut Shear Keys. Sheared Bearing Pads.
53-2206	118	R008.84	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2 ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2204	118	R008.34	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2 ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2205	118	R008.63	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2 ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2694G	126	R005.80	RTE 126/ 5 SEP	Approach settlement. Minor spalls at column tops. Shear keys are cracked w/ some spalling. [EB: Moderate damage @ abuts. Spalling @ top of column]
53-0015	126	8.2	SFK SANTA CLAR	Sheared anchor bolts at abutments & bents 2&3 . Slight permanent displacement (approx. 1 1/2") has occured at both abutments. Bent 3 appears to have moved to the norh 1". Top of ret. wall adjacent to girders cracked due to lateral movement
53-1345F	134	.04	RIVERSIDE DR U	All (A1) keeper plates sheared (lower); (A3) parapet wall needs repair, rt ext shear key failed, rail displaced, lower brg keeper plates sheared.
53-1452F	134	.03	RIVERSIDE DR U	Abut 1 lower keeper plates sheared; Abut 3 L&R ext key sheared, curb spalled
53-1493S	134	0	RIVERSIDE D OC	(Both abuts) All keeper plates failed, all bent cols minor spalled. Col spalled. Abut. 1 right curtain wall cracked, curb spalled. Joint seals failed.

Table 2. continued

Bridge #	Rte	Post mile	Bridge Name	Description of Bridge Damage
53-t907G	t34	R008.88	NW CONN OC	Deck overhang spalls at hinges. Spans 14L and 22L diaphragm, bearing and hinge restrainer damage.
53-1280	134	2.24	OLIVE AVE OC	Abut keeper plate failed
53-1276	134	t.36	FORMAN AVE UC	Abut t Lt side parapet/ shear key failed
53-1790H	134	R005.67	LA RIV BOH	"A" seals torn for entire transverse length near E. side of str. Alum. rails separated adjacent to hinge. Crack at west abutment face.
53-1024R	t34	L009.9t	FIGUEROA ST UC	Abut 1 keeper plates failed & rt. ext. key cracked; Abut 3 keeper failed. Cracks in abut. 1.
53-1024L	134	L009.9t	FIGUEROA ST UC	Abutment (both) keeper plates have sheared.
53-1023R	134	L009.72	MONTE BONITO U	Abut. 1 -Right ext. shear key cracked.
53-19t7F	134	R009.04	SOUTH CONN OC	E Abut Shear Key Damage
53-1272	134	0.35	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1493S	134	0.00	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1336R	t34	0.01	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-2033	t38	5t.06	PEARLAND UP	High Load Hit, unknown damage
53-1960F	14	R024.73	RTE 14/5 SOH	Spans 1 & 2 collapsed (Southern end); Collapsed spans have been demo.; Contr. cleaning up
53-1964F	14	R024.97	NORTH CONN OC	Spans 1 &2 collapsed (most north. span demolished), Span 3 broken stirrups, Span 4 hinge damage with 2 to 4 inches of bearing, minor damage all hinges.
53-2200S	14	R030.8t	RTE 126 /14 SEP	Failed column. Concrete cracks @ WW & abut. backwall. Conc. broken @ hinges. Minor cracks and spalls @ top of column (DBR).
53-1936R	14	R025.13	SIERRA HWY UC	Abut. 1 rt. W.W. (minor spalling).
53-2171	14	R030.55	CEDAR VL WY OC	Conc. spalling north column, south face @ Bent 2, west side abut. spalls.
53-1960F	14	R24.77	RTE 14/5 SOH	A both hinges the Hinge restrainers, diaphragms & equalizing bolts @ both hinges failed. H3 (diaphragm punching damage visible (DBR). shear key failure & backwall spalling at abut. 9. 1 of 4 restrainers a H1 failed (span 2), 2 of 4 rest
53-2166R	14	R030.90	VIA PRNCSSA UC	Wingwalls damaged due to movement of shoulder slab at Abut.
53-2166L	14	R030.90	VIA PRNCSSA UC	Wingwall damaged due to movement of shoulder slab (E. side of S. Abut & W. side of N. Abut)
53-220tK	14	R030.91	VIA PRNCSSA UC	Abut. and rail damage at N. Abut E. side & So. Abut W. side due to movement of the shoulder slab.
53-2027R	14	R03t.88	SANTA CLARA RI	2 hinges opened 4", conc breakage of hinges seats & rails, distortion of filling mat'l, minor spalls at top of col (bents 5&6).
53-2027L	14	R03t.88	SANTA CLARA RI	2 hinges opened 4", concr. breakage of hinges seats & rails, distortion of filling mat'l, minor spalls at top of col (bents 5&6).
53-t963F	14	R24.82	SOUTH CONN OC	Damage to hinge1, span 4 (2-3" seat remain). 6" movement @ abut, severe damage. Approach slab off seat w/ no fill beneath.
53-1962F	14	R024.81	TRUCK CONN OC	Minor cracking and spalling at abut 1 (South End) . Minor spall on barrier at 1st hinge.
53-2029L	14	R031.62	HUMPHREYS OH	Shattered concrete at junction wingwall - abutment wall acute corners - SE & NW.
53-2029R	14	R031.62	HUMPHREYS OH	Spalls at rail and wingwall at abutments.
53-2076L	14	R028.08	PLACERITA R UC	Minor spall at southern abutment. Rebars are exposed.
53-2076R	14	R028.08	PLACERITA R UC	Spalling of concrete at the abutment . It seems the spalled concrete is an old patching.
53-1964F	14	R24.97	SOUTH CONN OC	Damage to hinge1, span 4 (2-3" seat remain). 6" movement @ abut, severe damage. Approach slab off seat w/ no fill beneath.
53-1644	170	R015.63	CHANDLER BV OH	Minor crack at center approach railing
53-0490	170	R018.65	WHITSETT AV OC	Perm. Disp. at Abuts.(5"); Plastic Hinging at B-2 & B-4 Cols; Struc. has rotat. Count.-clk. wise
53-1344	170	R014.78	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1t22G	170	R020.52	RTE 170/5 SEP	Joint seal failed A1, hinge, A7. Large spall near hinge in shoulder (10' x 2'). Four keeper plates broken at At.
53-1339F	170	R14.51	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1921F	2	R018.81	NE CONNECTR OC	Longitudinal disp. at abut, spalled shear key, abut/ret wall seperation, torn water stops at abut/wingwall joint. Diaphragm damage at span 3 (cell 3).
53-2104F	210	R006.08	RTE118/210 SEP	Spalling at hinge seats. Restrainer damage at span 3 (cells 1 thru 5), span 5 (cells 1 thru 5) span 8 (cells t & 4). Hinge movement,, bad seals on armored joints torn in tension.
53-1988F	210	R000.12	NORTH CONN SEP	Minor wingwall cracking at left side A1.
53-1925	210	R003.01	TYLER ST POC	Spalling @ Abut 1 seat. Approx 75% loss of bearing area.
53-2219K	210	R0t8.53	WALTONIA DR UC	1" movement @ both hinges. Minor crack @ departure AC. Joint seal type "B" is loose in joints.
53-1896	210	R003.57	ASTORIA ST POC	Cracking and spalling of abutment 1 seat. Approx. 30% loss of bearing seat.
53-2117	210	R007.16	TERRA BEL ST U	Appr. slab settled 2" in lanes t&2 at E. & W. Abuts. Shear keys are cracked per S1 3/3/94.
53-2009	2t0	R046.36	SAN DIMAS A UC	Settlement of N/B approach (AC - no slabs) and movement @ south end slope. Some Top of Col Spalls.
53-0302R	22	1.42	SAN GABRIEL R	Minor spalling at pier wall between rt & lt bridges
52-01t8	23	23.62	SANTA CLARA R	Minor to moderate shear cracks and spall in the pier walls. Moderate shear cracks in the top of pier wall #4 (west end) and top of pier wall #8 (east end). 24"L x 20"W spalls at top of pier wall #2 (east end) and top of pier wall #3 (east end)
53-1500	405	46.24	DEVONSHIRE UC	Minor damage; minor diag crack abut rt exterior key cracked at base - All MInor
53-1506	405	47.75	RINALDI ST UC	Bent 3 major damage. Horiz & vert cracks in closure wall. PJW excavated Bent 3 footing (1/23/94) only minor damage to piles. Not more than one pile lost.
53-1507	405	47.24	SAN FERN BL UC	Approach settlement< 14". Rail slamming and spalls. 2" sag at midspan. Abut & WW cracks to 1/8". Deck spalls @ joints.
53-0739	405	37.03	MULHOLLAND D O	Bearings damage at abuts; spalled on wingwall barrier; joint seal failure both abuts.EB & WB AC settlement.
53-t501	405	46.74	CHATSWRTH ST U	Approach fill settlement. Minor cracks & spalls at ext shear keys at B3R & B2R. Barrier rail spall at AtL. Vertical joints at abutment closure walls have shifted.
53-2216G	405	46.8	SE CONN OC	Severe damage at abut 1, spalls under 5 of 10 girders, from shear keys; most hinges have damaged bearings, restrainers & diaphragms; approach settlements & offsets; (Ref Br # 53-2212F Report - same abut) t. Severe damage at abutment 1;
53-1439	405	44.24	PARTHENIA ST U	Bt2 rt rail spalled; abut 4 north bound approached settlement. .
53-t255	405	25.93	JEFFERSON BV U	DAMAGE TO COMMON BENTS WITH BRIDGE NUMBER 53-185t. All ext. col. connection to bent caps 2,3,4 suffered damage. Col #7 @ B2 & B3 suffered the most damage.
53-0704	405	29.85	EXPOSITION OH	Spalls/ cracks in Col. 4, 5, 6, 7. Cracks at Bent caps 3, 5, 7.
53-1852F	405	25.91	SOUTH CONN OC	N Side Spall at Hinge Seat Extender Bolster.
53-1629F	405	29.62	NE CONNECTR OC	W. abut. rockers are out of position, keeper plates broken. Metal tube railing A abut. pulled appart & butted against next rail sect. @ E. abut. 1'x1' spall in safety walkway. Span 3 hinge restrainer damage in Cell 1.
53-0704F	405	29.85	EXPOSITION OH	@Bt, span 1 has 2" movement toward B2. no damage??
53-1250	405	23.71	LA CIEN BV S O	Abut. Brg. damage; keeper plates sheared off
53-t630G	405	29.43	SW CONNECTR OC	Abut Rockers and Keepers are out of place. Bolster damage.
53-2211	405	46.83	RT 405 t18 SEP	Vertical cracks at bent walls. Diagonal cracks at columns. Incipient spalls at abutment shear .
53-0740	405	38.59	SEPULVEDA BV U	One spall at the overhang soffit @ B2 (1'x3')
53-1362	405	4t.27	W VAN NUYS OH	Minor cracks at abutment t.

Table 2. continued

Bridge #	Rte	Post mile	Bridge Name	Description of Bridge Damage
53-1449	405	41.36	VICTORY BV UC	Bearing pad delamination at Bent 2 (face of bin abutment).
53-1490	405	36.72	RIMERTON RD OC	Minor damage. Crack in closure wall right side A1.
53-1638G	405	29.42	SEPULVEDA B UC	2' of Sidewalk at N'ly rail broken over east abutment.
53-0706	405	30.18	EXPOSITION OH	Spalls/ cracks in Col. 4, 5, 6, 7. Cracks at Bent caps 3, 5, 7.
53-2217H	405	46.64	RT 405 118 SEP	Vertical cracks at bent walls. Diagonal cracks at columns. Incipient spalls at abutment shear .
53-1797L	5	R047.83	GAVIN CANYON U	Spans 2 & 4 collapsed, as of 11:15 AM 1/18/94 being removed
53-1117	5	34.65	TUXFORD ST UC	Minor damage, cracking. Keeper plate bolts sheared at abut 3.
53-1796	5	R046.58	WELDON CYN OC	Light cracks top of column @ bent 2. Minor cracks @ A1, left horiz. cracks top B7 col., incip. corner spall top A3 right, 1/16" diag. crack @ top A3 left (DBR)
53-0687L	5	R053.70	SANTA CLARA R	Abut 1 backwall cracked, both abutments have bearing pad / anchor bolt damage, So.E of Abut 8 restrainer cables failed, cracks in all piers (P7 heaviest damage). Some local buckling of stiffeners and cross frames..
53-1989F	5	R 44.01	SW CONNECTR OC	Shear key spalls. Minor spalls @ Bents 2 & 3. Insufficient seat width @ Abut 1. Superstructure lower than approach by 11/4" - 4". Longitudinal gaps in abuts 3 $^{3}/_{4}$" - 6 $^{1}/_{2}$".
53-1797R	5	R047.83	GAVIN CANYON U	Spans 2 & 4 collapsed, as 11:15 AM 1/18/94 being removed
53-2329G	5	39.31	SOWEST CONN OC	Abut cracks, approach slab settlement, failed joint seal at N. abut, crack in entire length of col. Girder bearing damage at hinges at span 2 (cells 1 & 5), span4 (cells 1 & 5) and span 6 (cells 1 & 5). Restrainer damage at span 6 (cells 1
53-1986	5	R044.43	BALBOA BV OC	Minor column damage, approach slab buckled
53-1985F	5	R044.01	RTE 210/5 SEP	Minor to moderate damage at both abuts. Shear keys slightly damaged. Spalls at hinge joint.
53-1990G	5	R043.83	SAN FERN RD OH	Approach slab rotation. Joint seals failed (both abuts). Spalls at abut 1. John Bither assigned a tenative B-PS&E of 3/18/94.
53-1128	5	39.19	PACOIMA WASH	Failed columns at B2 & B3, significant column damage on most of the columns of both bents.
53-1548	5	41.55	RTE 5T/405 SEP	Minor cracks at two columns.
53-1068	5	23.66	GLENDALE BV OC	2" horizontal superstructure rotation. Minor sidewalk spalls
53-0387	5	R50.80	BUTTE CANYON	Spalls and cracks @ A1&6.
53-0687R	5	R053.70	SANTA CLARA R	Spalls at both abuts, @ A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Some local buckling of stiffeners and cross frames..
53-1815	5	R052.47	VALENCIA BV OC	Abut 1 diaplaced approx 6" left of orig., A3 is 1" left of orig., spalls at both abuts, 27" water line supports damaged. Damaged roller brgs. Retrofit will not be done by S14, just repairs per Fritz Hoffman 3/9/94.
53-2057	5	R051.44	MCBEAN PKWY OC	Minor spalls at both abutments.
53-1807	5	R056.12	HONOR RHO R OC	Cracks and spalls at abutments and bents. Gdr seats cracked at gdrs #1 & 4.
53-1809	5	R056.60	HASLEY CYN R O	Shear cracks @ B2 on span 1 & 2 sides, both L & R columns.
53-1087	5	29.16	OLIVE AVE OC	Minor spalling at bent joints where there was debris in joints. Broken keeper plate bolts.
53-1088	5	29.39	MAGNOLIA BV OC	Minor pier cap spall under a bearing. Broken kepper plate bolts.
53-1908L	5	R059.49	LK HUGHES R UC	1 1/2 " or less settlement at both approaches.
53-1984L	5	R044.87	W SYLMAR OH	Additional damage to all shear keys and expansion joints due to after shocks.
53-1984R	5	R044.87	W SYLMAR OH	Spalls at hinges and abutments. Shear keys have failed. Additional damage to all shear keys and hinges due to after shocks.
53-1333	5	18.52	ECHANDIA OH	Sheared Brg Keeper Bolts at A1 N.Minor Spalling of R & L Rail at A1.
53-1783	5	R050.33	PICO LYONS OC	Cracks / spalls, bearing & restrainer damage @ abut 1. Severe cracks, cracked girder web & restrainer damage @ abut 3. Minor cracks @ col 2, Bent 2. Retrofit will not be done by S14, just repairs per Fritz Hoffman 3/9/94.
53-2330F	5	39.36	NE CONN OC	Restrainer and bearing damage at span 5 (cell 1) and restrainer and diaphragm damage at span 5 (cell 3). Deck spalling @ abutment joints.
53-2346F	5	39.26	PACOIMA WASH	Abut 1 shifted @ right & spalled 3 ft of concr. near deck level adjacent to WW
53-1133	5	41.57	RTE 5/405 SEP	Minor cracking at Abut 1 Wingwall
53-1132	5	40.46	RINALDI ST UC	Miinor cracking in soffit near A-1; Several cracks and spalls in lt. and rt. ext. diaphragms at A-1. Right bin wall near B-3 pushed 2" toward A-1. Minor damage at tube rail at abut 1.
53-1130	5	39.98	BRAND BLVD UC	Shear cracks and spalling in both external shear keys at Bts. 2 & 5.
53-1126	5	38.5	VAN NYS BL UC	Apparent broken water line washed out left side of A2 undermining bin walls & 2 LF of pile cap.
53-0848R	5	C045.49	SIERRA HWY SEP	Bearing, shear key and pedestal damage, both abutments. Large deck crack at widening closure pour. Some barrier damage.
53-0730	5	R043.84	SAN FERN RD OH `	Internal and external shear key failures. Minor top of column fractures.
53-0848G	5	C045.49	SIERRA HWY SEP	No Damage. Minor shear key damage at both abutments.
53-1115	5	42.65	ROXFORD ST UC	Minor cracking at left curtain walls and right side of Abut 1 shear key. Minor approach settlement.
53-1181S	5	24.61	GRFTH PK OR OC	Joint seal (Type A) damage at hinge in span 3.
53-1304	5	17.56	FOURTH ST UC	No Damage.
53-2327F	5	39.30	SOEAST CONN OC	Moderate damage at both abutments. Restrainer and bearing damage at span 6 (cells 1 & 4) and span 8 (cells 1 & 4). Bearing damage at span 11 (cells 1 & 4). Changed rte & PM for Jerry.
53-1332F	5	18.53	ECHANDIA OH	Minor. Large diagonal crack in curtain wall at side of A-9 . Also incipient spalling. 1' x 1' spall at REOD overhang at abut 9. Minor spall at left rail at abut 1.
53-1316	5	18.38	S CONNECTOR UC	MInor . Slight cracks ext. shears both A-1 and A-2.
53-1312	5	18.78	MISSION RD UC	Spalled A1 rt. diaphram/ww rt. joint seperated - ww not plumb - top pulled away 4"+or- -no settlement of app. fill.
53-1359R	5	17.21	HOLLENBECK LAK	A1 bearing keeper plate bolts sheared.
53-0368	5	18.96	ALHAMBRA AV OH	Minor spalls at abut 5 under girders.
53-1317F	5	18.62	MISSION RD R U	A1 backwall moderately spalled - many rocker brg. keeper plates damaged with sheared bolts.
53-1792L	5	R049.03	CALGROVE BV UC	Appr Pvmt & Shoulder Displacement. A1 Appr Lanes Settled 2". A1 Rt Appr Shoulder Heaved & Buckled & PCC Shoulder Spalled at Bridge. A1 Lt Appr Shoulder AC Settled 8" - 12" w/18" voids. A3 Rt Appr Shoulder Settled 3". A1 Rt & A3 Rt Slope Pav
53-1222K	5	36.34	SHARP AVE ONRP OC	At abutment 4, total 4 locations, the anchor bolts are sheared off for the lower keeper bar for the rocker bearing. There are 3 minor spalls (30cmx30cm area) on the soffit of the EQ restrainer outrigger.
53-1110	5	31.23	BUENA V-WIN UC	No Damage Approach slabs to be replaced EA 1Q7501
53-1118W	5	35.01	LANKERSHIM PP	Hairline Cracks in Backwalls. No damage per Makoto Ogata on 3/9/94.
53-1359L	5	17.21	HOLLENBECK LAK	1' x 2" spall at A1 lt edge of dk. 1 LF exp. reinf.
53-1626G	5	R055.48	RTE 126/5 SEP	Cracks at abutment / soffit interface. Minor top of column cracks & spalls. A5 continuous stub wall spall.
53-1424	5	20.31	ELYSIAN VIAD	Minor/mod. B8 shear key minor spalls.
53-1792R	5	R049.03	CALGROVE BV UC	Appr Pvmt & Shoulder Displacement. A1 Appr Lanes Settled 2". A1 Rt Appr Shoulder Heaved & Buckled & PCC Shoulder Spalled at Bridge. A1 Lt Appr Shoulder AC Settled 8" - 12" w/18" voids. A3 Rt Appr Shoulder Settled 3". A1 Rt & A3 Rt Slope Pav

Table 2.. continued

Bridge #	Rte	Post mile	Bridge Name	Description of Bridge Damage
53-1625L	5	R053.55	SANTA CLARA R	Spalls at both abuts, @ A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Some local buckling of stiffeners and cross frames
53-1625R	5	R053.55	SANTA CLARA R	Spalls at both abuts, @ A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Some local buckling of stiffeners and cross frames
53-0848L	5	C045.49	SIERRA HWY SEP	Bearing, shear key and pedestal damage, both abutments. Large deck crack at widening closure pour. Some barrier damage.
53-1728	60	R003.88	BELVEDERE POC	Minor spall at top of bent column adjacent to WB Rte 80.
53-1717H	60	R003.26	NE CONNECT OC	Abut 12 Keeper Plate Anchor Bolts Sheared. Rocker Bar Fell Over.
53-0075L	60	R001.26	WHITTIER BV UC	Shear Key Spall. At Lt Shear Keys Gdrs #4 & 5. Sections Approx 1'X1'X1.5'.(12" x 12" x 1'-6"). The stiffeners which are connected to the cross bracing at the abutment have moved 0.64 cm (1/4").
53-0081	60	R001.48	LORENA ST OC	At Keeper Plate Anchor Bolts Sheared. Same damage at A3.
53-1987F	71	R000.58	E CONNECTOR OC	Crack in support side of hinge @ Bent #2.Crack width is about 0.5" at the top and tapers down to 0" at the bottom. Crack runs vertically 6" from the edge of the hinge seat.
53-1714G	710	24.61	SE CONN OC	No damage per DBR. Steel rockers damaged.
53-1716F	710	24.64	NW CONN OC	NO damage per DBR. Steel rockers damaged.
53-1851	90	2.54	RTE 90 405 SEP	Numerous shear cracks and some spalling at common bent with Br # 53-1255. Multicolumn bent @ median has extended damage to top of bent caps on transverse internal shear keys.
53-1854G	90	2.55	NW CONNECT OC	Minor abutment spalls. No damage per Makoto Ogata on 3/9/94.
53-1855F	90	2.73	JEFFERSON B UC	Minor damage - barrier rail pipe@ hinge slipped out of sleeve.
53-2240	91	R011.64	RTE 91/710 SEP	Minor rail and WW damage due to rotation of 38 degrees skewed S. abut. 2 S rail pocket spls @ SW end. ± 4" bow in ± 20' metal rail; ± 1' x 1' spl in upper corner SW ww; ± 1/2" crack from bot ext gdr ± 2' long (DBR)

DAMAGE TO BRIDGES WITH SEISMIC RETROFITS

After the 1971 San Fernando earthquake, Caltrans began its first bridge seismic retrofit program. These retrofits were mostly to prevent the superstructure from falling off its supports. After the 1989 Loma Prieta earthquake, Caltrans began the second seismic retrofit program. These retrofits addressed a wider range of problems and were more sophisticated in their approach. Table 3 indicates what retrofit strategies are available and when they began being used. About halfway through this second retrofit program, the 17 January 1994 Northridge earthquake occurred. There were 132 bridges in the area of shaking that had a post San Fernando earthquake retrofit. Several of these bridges suffered major damage including Gavin Canyon Bridge and portions of the 14/5 Interchange. There were 63 bridges in this same area that had a post Loma Prieta retrofit. None of these bridges suffered significant damage. The most serious damage was on the Southeast Connector Overcrossing Bridge 53-1637F (Photo 11). This is a long, tall, prestressed con-

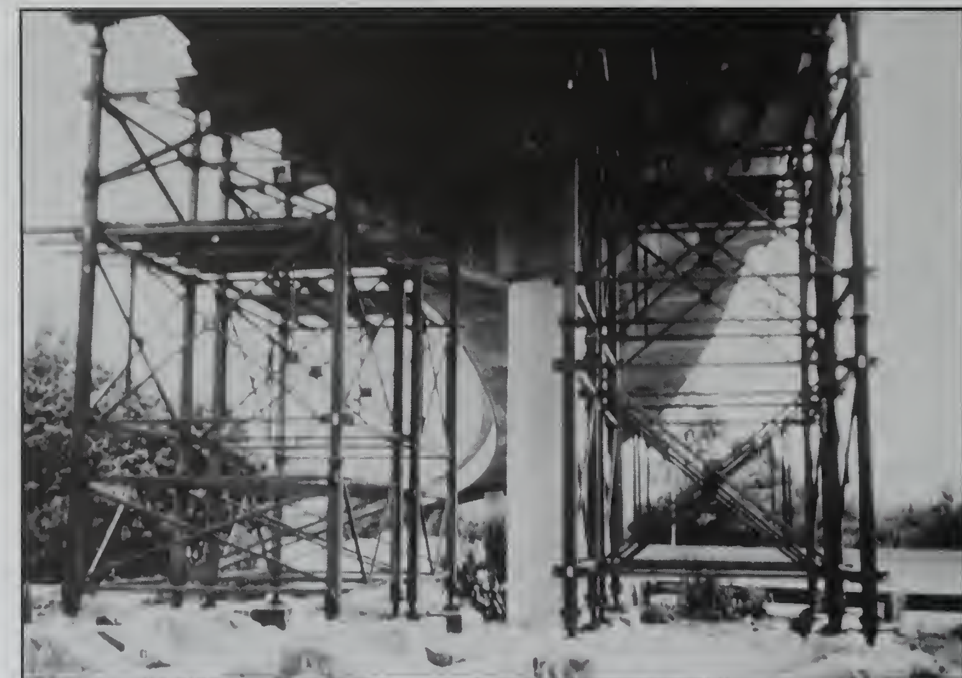


Photo 11. Damage to the Southeast Connector Overcrossing Bridge (53-1637F).

Table 3. Summary of seismic retrofit strategies.

Date of Retrofit	Superstructure Stability	Substructure Strength	Substructure Ductility	Substructure Stiffness	Bridge Energy
OLD <1989	Restrainers Shear Keys Bearing Replacements Catcher Blocks			Isolation	Dampers Fuses
NEW >1989	Pipe Seat Extenders	Footing Retrofits Abutment Retrofits (Tiebacks, Large Diameter Piles, Waffle Slabs) Column Retrofits (Shear Walls & Super columns)	Steel Column Shells Column Fiber Wraps	Abutment Retrofits	

Table 4. List of local agency bridges eligible for Federal funds after the Northridge earthquake

PROJECT # REPORT #	EA	DT	AGENCY	CO-RTE-PM	LOCATION	F.CLASS	ON FED HWY?	EST ER OPENING AMT	ESTIMATED RESTORATION AMT			TOTAL ESTIMATED AMT	TOTAL OBLIGATED AMT
									PE	CE	CONST		
•ER-2600(006) •MN-LACO-1	928894	07	Los Angeles County	LA - 0 - CRS	McBEAN PARKWAY OVER SANTA CLARA RIVER (1.20 MILES E OF I-5) Bridge	U-MA	yes	530,000				530,000	496,400
•ER-2600(008) •MN-LACO-2	928895	07	Los Angeles County	LA - 0 - CRS	SIERRA HWY. (NB): (0.5 MI S OF SOLEDAD CANYON RD. OVER SPTC. Sierra Hwy OH bridge.	U-OPA	yes	5,000	10,000	15,000	100,000	135,000	17,705
•ER-2600(013) •MN-LACO-5	927551	07	Los Angeles County	LA - 0 - CRS	WHITES CNYN RD BRIDGE OVER SANTA CLARA RIVER & OVER SPTC. ALSO VIA PRINCESSA : SIERRY HWY TO MAY WAY.	U-MA	yes	105,120				105,120	105,120
•ER-2601(009) •KK-SCta-1	928911	07	Santa Clarita	LA - 0 - SCTA	SAND CANYON RD. BRIDGE APPROACHES OVER SANTA CLARA RIVER.	R-MJC	yes	325	312	468	3,122	4,227	
•ER-2601(010) •RLC-SCta-8.1	928912	07	Santa Clarita	LA - 0 - SCTA	SIERRA HWY 500' S SOLEDAD 500' N SOLEDAD; RR BRIDGE; BRIDGE OVER SANTA CLARA RIVER	U-OPA	yes		1,254	2,055	12,545	15,854	
•ER-2602(060) •JD-LA-3		07	Los Angeles	LA - 0 - LA	WILBUR: ENTIRE LENGTH. bridge	U-MA	yes	50,000	14,059	21,088	90,591	175,738	
•ER-2603(001) •DB-LA-1	928921	07	Los Angeles	LA - 0 - LA	NORDHOFF ST. BRIDGE OVER SP R/R TRACKS BETWEEN CORBIN AVE. & TAMPA AVE.	U-OPA	yes	587,000				587,000	278,800
•ER-2603(002) •	9289[illegible]3	07	Los Angeles	LA - 0 - LA	WILBUR AVE. @ COLLINS ST. PEDESTRIAN OVERCROSSING.	U-MA	yes	64,700				64,700	84,100
•ER-2603(003) •NB-LA-7	928983	07	Los Angeles	LA - 0 - LA	AVE 43 BRIDGE OVER ARROYO SECO CHANNEL & PASADENA FWY.	U-MA	yes		300	400	3,000	3,700	91,412
•ER-2603(004) •MN-LA-1	92898[illegible]	07	Los Angeles	LA - 0 - LA	BALBOA BL (EAST RDWY) BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND BURBANK BL.	U-OPA	yes		1,000	1,500	10,000	12,500	
•ER-2603(005) •MN-LA-2	92898[illegible]	07	Los Angeles	LA - 0 - LA	DEVONSHIRE ST BRIDGE OVER PACOIMA WASH DIVERSION CHANNEL AT ARLETA AV.	U-OPA	yes		1,500	2,200	15,000	18,700	32,085
•ER-2603(006) •MN-LA-3	928986	07	Los Angeles	LA - 0 - LA	FRANKLIN AV BRIDGE BETWEEN ST GEORGE ST AND MYRA AV.	U-MA	yes		1,500	2,200	15,000	18,700	
•ER-2603(007) •NB-LA-1	928987	07	Los Angeles	LA - 0 - LA	GRAND AV BRIDGE BETWEEN 2ND PL AND 4TH ST	U-OPA	yes	1,600	5,500	8,250	55,000	70,350	0
•ER-2603(008) •MN-LA-4	928988	07	Los Angeles	LA - 0 - LA	LA TIJERA BL BRIDGE OVER SPRR & CENTINELA CREEK BETWEEN THORNBURN ST. & SAN DIEGO FWY.	U-OPA	yes		2,300	3,450	23,000	28,750	0
•ER-2603(009) •NB-LA-4.1	928989	07	Los Angeles	LA - 0 - LA	LINDLEY AV BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND ERWIN ST.	U-MA	yes		1,660	2,490	16,600	20,750	82,774
•ER-2603(010) •NB-LA-2.1	9289[illegible]0	07	Los Angeles	LA - 0 - LA	MAGNOLIA BL BRIDGE OVER TUJUNGA WASH BETWEEN BELLAIRE AV AND COLD WATER CANYON.	U-MA	yes		928	1,392	9,280	11,600	0
•ER-2603(011) •MN-LA-9	928991	07	Los Angeles	LA - 0 - LA	MASON AV BRIDGE OVER LA RIVER BETWEEN HART ST AND VANOWEN ST	U-MA	yes	1,000	3,000	4,500	30,000	38,500	34,349
•ER-2603(012) •MN-LA-5	928992	07	Los Angeles	LA - 0 - LA	NATIONAL BL (NORTH) BRIDGE OVER BALLONA CREEK @ JEFFERSON BL.	U-OPA	yes		2,000	3,000	20,000	25,000	
•ER-2603(013) •NB-LA-6	9289[illegible]3	07	Los Angeles	LA - 0 - LA	RESEDA BL BRIDGE OVER LA RIVER BETWEEN KITTRIDGE ST AND VICTORY BL.	U-OPA	yes		880	1,320	8,800	11,000	0
•ER-2603(014) •MN-LA-6	928994	07	Los Angeles	LA - 0 - LA	SAN FERNANDO RD BRIDGE OVER TUJUNGA WASH BETWEEN TRUESDALE ST AND BRANDFORD ST.	U-OPA	yes	1,000	2,300	3,500	23,500	30,300	
•ER-2603(015) •MN-LA-7	9289[illegible]	07	Los Angeles	LA - 0 - LA	TAMPA AV BRIDGE OVER LA RIVER BETWEEN KITTRIDGE ST AND VICTORY BL.	U-OPA	yes		2,000	3,000	20,000	25,000	
•ER-2603(016) •NB-LA-5	928996	07	Los Angeles	LA - 0 - LA	VANOWEN ST BRIDGE OVER LA RIVER BETWEEN OSO AV AND MASON AV.	U-OPA	yes		2,800	4,200	28,000	35,000	
•ER-2603(017) •MN-LA-8	928997	07	Los Angeles	LA - 0 - LA	WHITE OAK AV BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND ERWIN ST.	U-OPA	yes		500	750	5,000	6,250	
•ER-2603(018) •NB-LA-3	9289[illegible]8	07	Los Angeles	LA - 0 - LA	WINNETKA AV BRIDGE OVER LA RIVER BETWEEN ARCHWOOD ST AND GILMORE ST	U-OPA	yes		800	1,200	8,000	10,000	0
•ER-2603(020) •MN-LA-10	927530	07	Los Angeles	LA - 0 - LA	BARHAM BLVD. BRIDGE OVER LA RIVER	U-OPA	yes	148,000				148,000	148,000
•ER-2603(021) •MN-LA-11		07	Los Angeles	LA - 0 - LA	VICTORY BLVD. BRIDGE OVER LA RIVER BET. LINDLEY & ETIWANDA AVE.	U-MA	yes		3,440	5,160	34,400	43,000	
•ER-2605(002) •MN-VEN-1	928975	07	Ventura County	VEN- 0 -	SANTA SUSANA PASS ROAD BRIDGE AT RAIL ROAD.	R-MA	yes		1,200	900	9,500	11,600	11,600
						Statewide Summary:		$1,493,745	$59,233	$88,023	$540,338	$2,186,339	$1,382,345

crete bridge with a retrofit that includes steel shelled columns and restrainer and abutment work. The bridge has hinges supported on columns. During the earthquake, the restrainers holding the hinges together smashed the hinge diaphragms and surrounding concrete. The bridge was closed to traffic until shoring was provided around the column. If the second retrofit program had been completed at the time of the Northridge earthquake, it is likely that only one or two bridges would have suffered severe damage.

DAMAGE TO CITY AND COUNTY BRIDGES

In contrast to the many state owned bridges that suffered damage, there was very little damage to any city or county bridge during the Northridge earthquake (Table 4). Only a few local bridges suffered significant damage from the earthquake. The most serious damage occurred to Wilbur Avenue Pedestrian Overcrossing (53C-1387). This reinforced concrete, box girder bridge is 3 miles south of the epicenter in the town of Tarzana. During the earthquake the bottom of the columns were severely distressed and it appeared that a few more cycles of movement would have knocked them over.

The Sierra Highway Overhead (53C-1776R) is an older concrete T-beam Bridge. It was retrofit with cable restrainers at the hinges. During the earthquake, a transverse restrainer broke, and the end diaphragms, which sat on footings, were smashed.

McBean Parkway Bridge(53C-1840) is a precast I girder bridge on pier walls and seat type abutments. During the earthquake the superstructure smashed through the backwall and about 6 inches into the soil.

The Old Road Bridge (53C-0327) had large steel plate girders attached to deep floor beams on pinned bearings. During the earthquake, one floor beam buckled and the other floor beam tore the bearings out of the piers.

DAMAGE TO STEEL BRIDGES

There were several steel bridges that experienced damage during the Northridge earthquake. Most of this damage was from the superstructure banging against the abutments. In many cases damage to anchor bolts and bearings also occurred. Better connection details between steel superstructures and concrete substructures may eliminate some of this damage. As mentioned above, there was also a tendency for the steel floor beams to experience distress during the earthquake. All the seismic force is transferred by these diaphragms into the substructure.

Photo 12. Santa Clara River Bridge

The Santa Clara River Bridge (53-0687L) is a highly skewed, 741 foot long, seven span structure. During the earthquake, many of the anchor bolts connecting the girders to the concrete piers pulled out (Photo 12). There was also banging and spalling of the abutments. The most interesting damage was cracking of the girders where they connected to the cross frames. The cross frames were staggered due to the bridge skew. These cracks were probably initiated through fatigue and propagated by the earthquake. It has long been known that staggered cross frames are a serious maintenance problem for steel bridges.

Pico-Lyons Overcrossing Bridge (53-1783) is a two span continuous plate girder bridge. During the earthquake the restrainers, anchor bolts, and bearings were damaged.

Other bridges with very minor damage include McBean Parkway Overcrossong (53-2057), Valencia Boulevard Overcrossing (53-1815), and the Old Road Bridge mentioned above.

SOIL BEHAVIOR RELATED TO BRIDGE AND HIGHWAY DAMAGE.

In general, it appears that foundation soil was not a significant factor in causing bridge damage during the Northridge earthquake. The one exception may have been at the Santa Monica freeway where softer soils may have amplified the earthquake motion. In general, the bridge sites were on medium sands over denser sands and sandstone. There were some layers of clay and silt at Route 118. However, weak soils did not play the sigmificant role they did during the Loma Prieta earthquake.

HIGHWAY DAMAGE

There was a great deal of highway damage as a result of the Northridge earthquake. As of May 1994, 122 million dollars was spent on highway repairs compared with 144 million dollars in bridge repairs. The highway costs included repair of the many bridge approaches that settled during the earthquake. The area of highway damage was even more widespread than the area of bridge damage, extending north of Castaic on I-5, south on Highway 405 to Ballona Creek, west on Route 126 to Fillmore, and east on Route 14 to Santa Clarita. Much of the damage occurred to highway slabs that buckled due to soil settlement and road slipouts caused by landslides. There was also damage to drainage pipes and culverts under highways. Highway 2 near La Canada had to be cleared of several minor landslides. A portion of Route 126 at the Los Angeles/Ventura county line was built on an ancient slide that required periodic regrading after the earthquake.

The most serious damage was settlement of bridge approaches, particularly on Highway 118. Other damage included soil heaves on I-5 from Castaic to the Hollywood freeway. There was also a slipout on I-5 on the 5 mile grade near Castaic. This caused damage to the highway and many of the drains under the highway . On Route 14 both north and south of I-5 the roadway buckled and was later covered with an asphalt blanket. There was a slough under a portion of Highway 14. At highways 405 and 5 in Granada Hills the pavement slabs buckled. There was a great deal of damage to the Santa Monica freeway due to soil movement. There was also significant damage to city and county roads. A landslide occurred on the Sierra Highway maintained by Los Angeles County near the 5/14 Interchange. Approximately 5 miles of the Santa Susana Pass Road maintained by Ventura County east of the Southern Pacific Station Museum was torn up. Automobile sized boulders were reported on the roadway and large sections of the road slid off. The approaches to the Nordoff Street overhead owned by the City of Los Angeles settled several feet.

GENERAL CONCLUSIONS

Severe bridge damage from the Northridge earthquake fits into two categories. In general, we saw damage caused by columns with inadequate lateral reinforcement. However, we also saw severe damage resulting from bridge geometry that exacerbated existing weaknesses. This damage was caused by:

- Short stiff columns next to long flexible columns in the same frame or in the same bent.
- Skewed bents and abutments that caused bridge frames to rotate off of their supports.
- Abutments with opposite skews that forced bridge movement in a weak direction.
- Column flares that significantly increased the plastic shear and stiffness of columns.
- Conditions such as columns cast into slabs that make one bent much stiffer than the other bents.

Many of these failures could have been prevented by using seismic retrofit strategies that existed at the time of the Northridge earthquake. However, Bull Creek and Mission Gothic bridges point to areas that may require more study. These bridges were reviewed and taken out of the retrofit program before the Northridge earthquake. Better screening methods are needed to identify bridges that can suffer severe earthquake damage. As built conditions need to be more carefully studied before a seismic retrofit is begun. Also, better analysis tools are needed to capture the behavior of skewed bridges, flared columns, and other geometric anomalies that may cause higher than expected loads on bridge members.

This is an extremely brief report on a very complicated subject. Much more information exists in the many large reports that have come out since the earthquake. In particular, the reports by the Earthquake Engineering Research Institute (EERI), the Earthquake Engineering Research Center (EERC), the National Center for Earthquake Engineering Research (NCEER), the National Institute of Standards and Testing (NIST), the Universities of California at San Diego and Berkeley, and Caltrans Post Earthquake Investigation Team (PEQIT) provide much more insight into bridge behavior during the Northridge earthquake. Professors Priestley and Seible of the University of California at San Diego provide results of structural analyses performed on many of the damaged bridges. A report on the performance of steel bridges was written by Professor Abolhassan Astaneh-Asl of the University of California at Berkeley.

Sanchez, R., 1995, Damage to dams under state jurisdiction: January 1994 Northridge earthquake and aftershocks through October 1994 *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p.187-194.

DAMAGE TO DAMS UNDER STATE JURISDICTION: JANUARY 1994 NORTHRIDGE EARTHQUAKE AND AFTERSHOCKS THROUGH OCTOBER 1994

by

Richard Sanchez[1]

INTRODUCTION

The Division of Safety of Dams (DSOD) inspected 105 State jurisdictional dams in southern California following the January 17, 1994 Northridge earthquake by January 21, 1994. Three additional dams were inspected the week of January 24, 1994 for a total of 108 dams inspected (Figure 1). These dams are located within 47 miles of the epicenter.

Thirteen dams in the area were found to have cracking and some movement. Most of this cracking and movement has been determined to be minor. Increased seepage was noted at the north dike of the Los Angeles Reservoir. The low level outlet of Lower San Fernando Dam was severely damaged. At Pacoima Dam, a joint opening at the left abutment thrust block and cracks in the left abutment appear to be the most significant damage. None of these 13 affected dams are a safety hazard at this time, although further surveys, investigations, instrumentation data reviews, and repairs are underway to ensure the safety of some of these dams.

Division staff conducted follow-up inspections of dams closest to the epicenter on January 31, February 1, March 22, and March 23, 1994 and again no significant damage was found that would represent an immediate threat to life and property.

SUMMARY OF DAMAGE AND REPAIRS

Listed below is a summary of the damage at the thirteen dams and follow-up actions.

Porter Estate Dam, Angeles County, near Chatsworth

Height: 41 feet	Reservoir Capacity: 135 Acre feet
Year Built: 1888	Storage during EQ: empty
Owner: Porter Ranch Development	Dam Type: Earth
Epicentral Distance: 3.3 miles	Dam No. 775

Longitudinal cracks up to 1/2-inch wide were found on the crest with transverse cracks up to 1/8-inch wide at each end of the embankment. A shallow slide extended 60 feet in length across the downstream slope with a one-foot vertical offset and slide cracks traceable to half way down the slope. A slide on the upstream slope extended 130 feet in length and slumped 6 inches at the crest; the slide extended down to the upstream berm (6 to 8 feet vertically). The reservoir remains empty by the use of seven 4-inch diameter pumps which is the normal operation for this detention basin. A follow-up inspection was conducted on January 31, 1994 and no additional damage was found. Repair application and plans submitted by owner's engineer, GeoSoils Inc., were approved by the Division on 08/17/94. Repair work that included excavating out the cracks and slide areas and rebuilding the embankment started 09/27/94 and was completed on 10/12/94.

---

[1] Department of Water Resources, Division of Safety of Dams, Sacramento, California

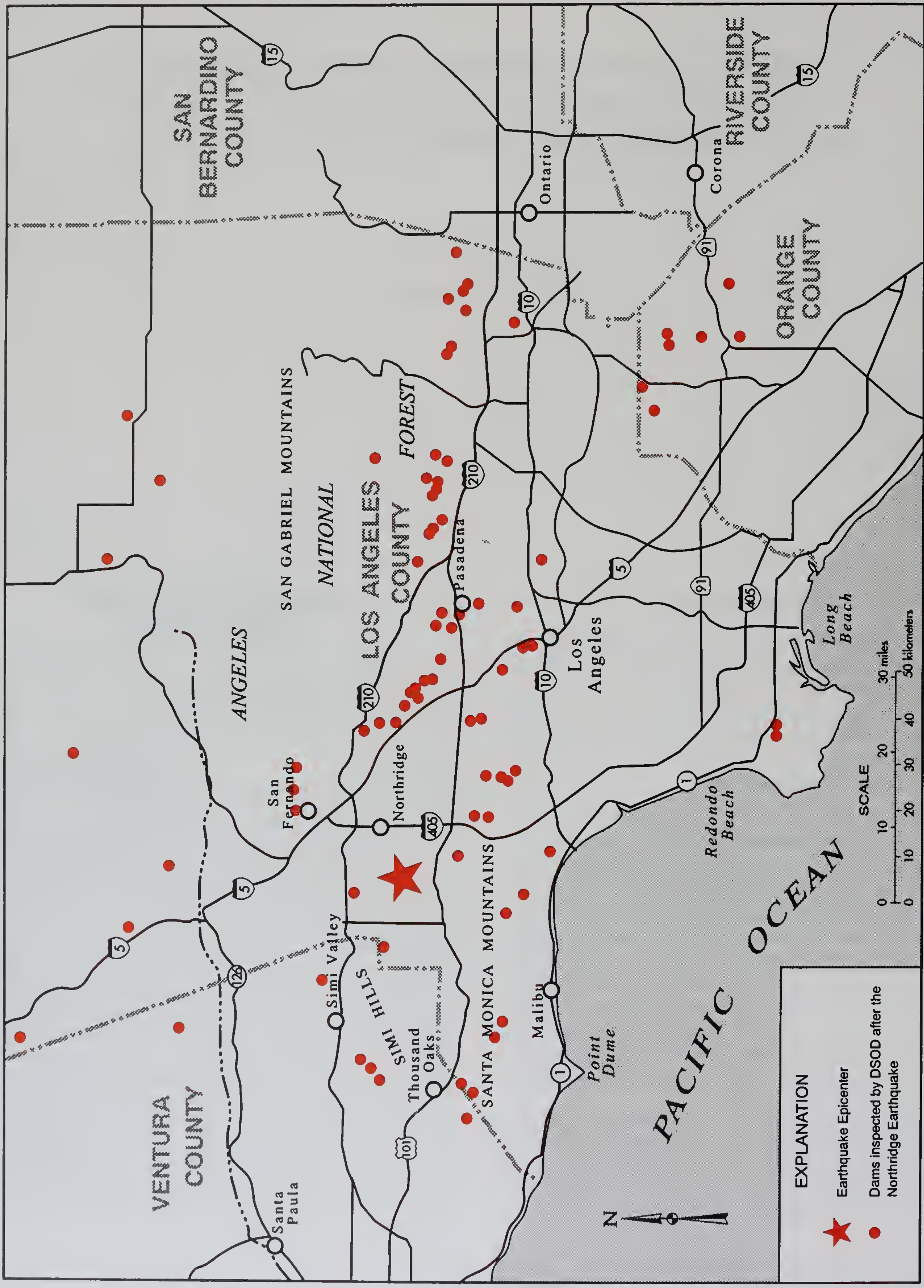


Figure 1. A total of 108 dams under State Jurisdiction were inspected for damage after the 1994 Northridge earthquake by the Department of Water Resources, Division of Safety of Dams. Thirteen dams were found to have some damage. All of the dams (shown by solid circles) are located within 47 miles of the earthquake epicenter (shown by red star).

Lower San Fernando Dam, Los Angeles County, near San Fernando

Height: 125 feet	Reservoir Capacity: 10,000 AF
Year Built: 1918	Storage during EQ: empty
Owner: City of Los Angeles	Dam Type: Hydraulic fill
Epicentral Distance: 5.9 miles	Dam No. 6-15

The reservoir is empty and serves as a flood control basin. Several two-inch-wide longitudinal cracks several hundred feet long were observed on the crest of the embankment. Some of the cracks could be probed up to 5 feet deep. Most cracking ran near the middle of the crest. Sand boils and a sink hole were observed upstream of the dam. The sink hole was trenched on 05/19/94 and the 96-inch diameter corrugated metal pipe low level outlet in the vicinity of the sink hole was found severely damaged (Photo 1). Surveys, dated April 15, 1994, of monuments and cracks were received 04/25/94. Maximum crest movement was -0.66 ft vertical and -0.33 ft horizontal, upstream (u/s) at Station #10, 45 ft. south of axis line. Maximum width of crest cracks was 3.6 inches. Observations of cracks during trench exploration on 06/14/94 found main crest cracks to be 15 feet deep. Owner will be submitting crack repair plans to the Division for approval. Observation well readings transmitted on 05/5/94, indicate a maximum rise of about three feet at well 64-C. Site preparation and excavation for outlet repair work completed during September 1994. Repair application and plans to replace damaged outlet with a new 185-feet long 96-inch diameter concrete outlet conduit approved on 10/21/94. Outlet repairs currently underway.

Photo 1. Damaged low-level outlet, looking toward reservoir, Lower San Fernando Dam. Photos courtesy of Division of Safety of Dams.

Los Angeles Reservoir Dam, Los Angeles Co., near San Fernando

Height: 130 feet	Reservoir Capacity: 10,000 AF
Year Built: 1977	Storage during EQ: Elev.1160
Owner: City of Los Angeles	Dam Type: Earth
Epicentral Distance: 6.1 miles	Dam No. 6-50

Hairline cracking was observed on the left end of the crest near the left abutment contact. Water surface level was at Elevation 1160, 15 feet below spillway crest at time of earthquake. Walkway to the outlet tower was separated about 2 inches over supports (north-south direction) and displaced about 16 inches horizontally (west-east direction), (Photo 2). Main dam settled 3.5 inches near the maximum section. Numerous cracks were discovered running longitudinally on the upstream slope asphalt concrete lining of the main dam, (Photo 3); more found when reservoir water surface lowered after earthquake. Transverse hairline crack 2 feet deep on left end of north dike embankment. This same crack partially sealed and was later observed to be only 6 inches deep on 02/24/94. Total seepage at the north dike increased from 97 gallons per minute (gpm) (01/13/94) to about 294 gpm (01/25/94) base on owner's 02/2/94 submittal. Individual

Photo 2. Damaged walkway bridge to outlet tower, Los Angeles Reservoir Dam.

Photo 3. Longitudinal crack on upstream slope of asphalt concrete lining of the main dam, Los Angeles Reservoir Dam .

follows: the west drain seepage increased from a rate of 68 gpm to 240 gpm; central drain seepage increased from 14 gpm to 37 gpm; and east drain seepage increased from 14 gpm to 17 gpm. Seepage on 05/13/94, reservoir stage (R.S.) at Elevation (EL.) 1165 was as follows: west drain 120 gpm; east drain 18.3 gpm; and central drain 16.3 gpm (total = 154.6 gpm). Total seepage at the main dam increased from 60 (01/3/94) to 77 (01/20/94) gpm. Maximum seepage increase at the main dam occurred at the east toe drain which increased 10 gpm. Seepage at H-1, H-2, H-3, H-4, and west drains increased slightly. Seepage at the main dam returned back to normal at 60 gpm on 02/17/94 (R.S. = El. 1150).

Embankment and foundation piezometric levels increased immediately after the earthquake but have gradually returned to normal. A maximum rise of 27.6 feet was measured at observation well #76-11 on the north dike. Survey of cracks received from owner on 04/25/94. Survey indicates surficial 2-inch wide maximum cracks on main dam and 1-inch wide maximum cracks on north dike. Visual observations of exploration trenches across cracks on both the main dam and north dike on 03/2/94 found cracks to be surficial. On 04/18/94, owner sealed cracks on both embankments with Polyflex Type III sealant, CRAFCO.

Maximum settlement of 3.5 inches at main dam crest occurred at Station 88+93. Maximum horizontal movement was 2.2 inches downstream (D/S) at Station 100+82, 240 feet south of axis, at the lower right abutment area of main dam. A maximum settlement of 1.2 inches and horizontal movement of 0.02 inch D/S occurred at the north dike crest Station 37+03. Owner's outlet tower bridge repair plans received on 06/10/94 and approved 06/17/94. Bridge repairs have been completed. North dike seepage continues to be monitored daily. Seepage data 08/18/94 notes north dike seepage at about 128 gpm, main dam total seepage at 74 gpm, and reservoir water level at Elevation 1164. No further work required.

Upper San Fernando Dam, Los Angeles County, near San Fernando

Height: 82 feet	Reservoir Capacity: 1,848 AF
Year Built: 1921	Storage during EQ: empty
Owner: City of Los Angeles	Dam Type: Hydraulic fill
Epicentral Distance: 6.4 miles	Dam No. 6-28

Photo 4. Several two-inch wide longitudinal cracks that were 40 to 60 feet long were found near the left abutment on the downstream slope, Upper San Fernando Dam.

The reservoir is empty and serves as a flood control basin. Transverse cracks found on the crest near the right abutment were up to 50 feet long and 3 inches wide. Several 2-inch wide maximum longitudinal cracks 40 to 60 feet long were found on the downstream slope and near left abutment (photo 4). Cracking was also observed at the spillway, and upstream slope of the dam. Monument and crack surveys dated April 15, 1994 were received 04/25/94. Maximum movement was -2.36 ft vertical at Station 8+00, 49.5 ft north of axis, and -0.6 ft horizontal, upstream, at Station 12+00, 49.5 ft north of axis. Observation well readings transmitted on 05/5/94 indicate a maximum rise of about 2 feet at well 68-B. Observation of cracks during trench exploration found main cracks on downstream slope near crest to be 5 feet deep. Owner plans to submit crack repair plans to Division for approval.

Schoolhouse Debris Basin Dam, Los Angeles County, San Fernando

Height: 38 feet	Reservoir Capacity: 19 AF
Year Built: 1962	Storage during EQ: empty
Owner: LA County, Dept. Power & Water (DPW)	Dam Type: Earth
Epicentral Distance: 8.6 miles	Dam No. 32-36

The reservoir is empty and serves as a flood control facility. Minor longitudinal cracking 50 to 100 feet in length was observed on the upstream and downstream slopes of the embankment. Seventeen small parallel cracks were found on the upstream face and another nine cracks were on the downstream face. A crack 15 feet downstream of the downstream toe appeared to line up with a pipeline. There was spalling at the left bridge stringer at the spillway chute with 0.16 foot of downstream movement on the structure. A spillway vertical wall joint opened approximately 1 inch. The owner sealed this open joint on 10/17/94.

Surveys to assess the cracking and movement at the dam and spillway have been requested. During a follow-up inspection of the dam on February 1, 1994 it was noted most of the cracks had disappeared. Owner's report dated 03/8/94 concludes cracks were minor. Owner plans to complete upstream concrete facing on dam during first half of 1995. Alteration application and plans for this work were received on 09/07/94 and are currently under review (9/94).

Lower Franklin Dam, Los Angeles County, near Beverly Hills

Height: 103 feet	Reservoir Capacity: 920 AF
Year Built: 1922	Storage during EQ: empty
Owner: City of Los Angeles	Dam Type: Hydraulic fill
Epicentral Distance: 11.3 miles	Dam No. 6-14

The reservoir is empty and serves as a flood control facility. A 1/4-inch wide transverse crack across the crest of the dam was discovered 15 to 20 feet from the left abutment, 6 feet east of Station 4+60. The crack was judged to be minor.

Surveys to assess movement at the dam have been completed. Survey data were received 08/30/94. Maximum crest settlement was 1.8 inches at Station 2+60. Crest settlement at Station 4+60 was 0.36 inch. Survey data and inspection observations indicate no additional work or investigations are required.

Pacoima Dam, Los Angeles County, near San Fernando

Height: 365 feet	Reservoir Capacity: 3,777 AF
Year Built: 1929	Storage during EQ: 1,000 AF
Owner: LA County, DPW (LACDPW)	Dam Type: Var. radius arch
Epicentral Distance: 11.4 miles	Dam No. 32-8

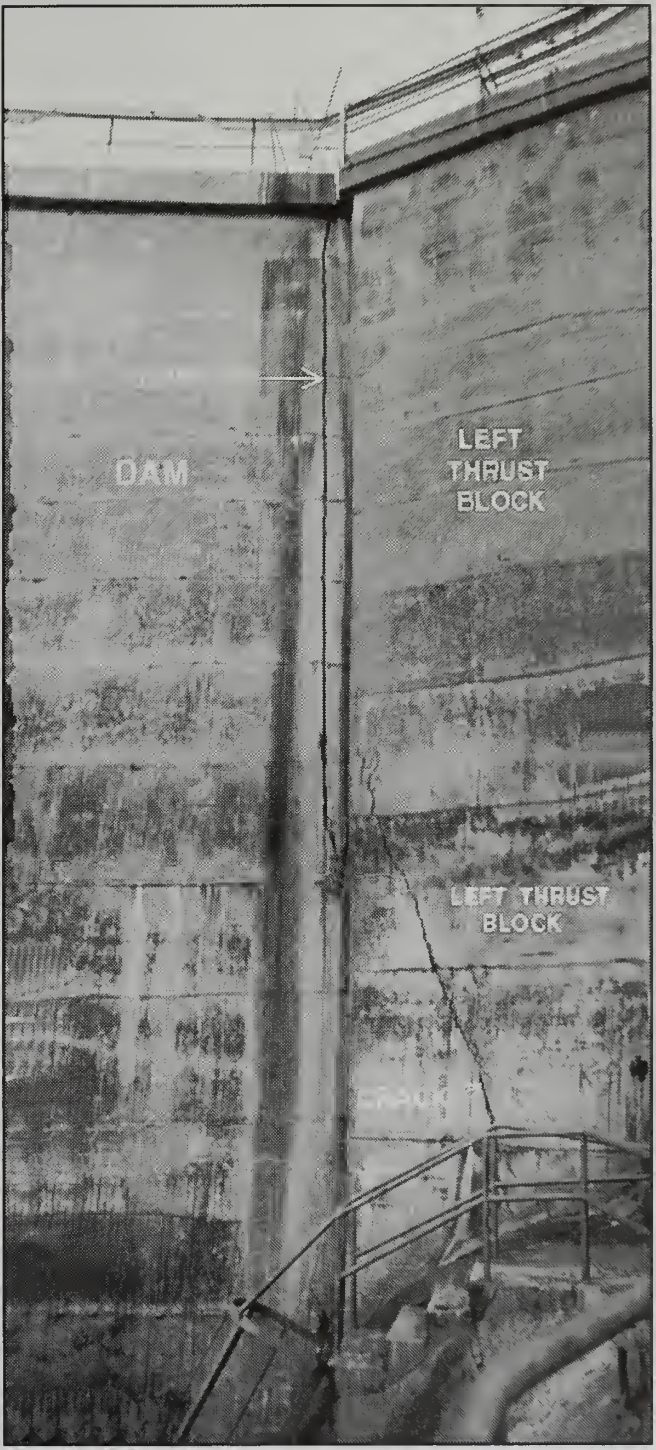


Photo 5. A joint between the left abutment concrete thrust block and the end of the dam opened approximately 2 inches at Pacoima Dam.

A joint between the left abutment concrete thrust block and the end of the dam opened approximately 2 inches (Photo 5). The left abutment concrete thrust block moved about 1-inch downstream relative to the dam crest. Gunite over the abutments was severely cracked (Photo 6), and the spillway chute was damaged (Photo 7).

Photo 6. Gunite over the abutments was severely cracked, Pacoima Dam

Surveys to assess movement at the dam were received 02/22/94. Pt. 0+10 on top of left thrust block moved 2.2 inches downstream (westerly) and minus 1.07 inches vertically relative to point 1+65 (which held) located on right end of the crest of the dam. Maximum horizontal displacement of 19.3 inches (S58°W) occurred at Pt. C2 on the left abutment and maximum vertical displacement of minus 14.1 inches occurred at point BM 030-20380 also on the left abutment. Stress data of the post-tension left abutment tendons, before and after the earthquake, were only available for tendons numbered 3, 17, and 35. On 10/8/92, tendon stress (percent of ultimate load) was at 63% for No. 3, 61% for No. 17, and 72% for No. 35. On 01/21/94 tendon stress was 65%(reduced to 61% on 01/26/94) for No. 3, 82% for No. 17, and 84% (reduce to 75% on 01/22/94) for No. 35. After 01/26/94 all liftoff tendons became inoperable, pressure o-rings have apparently failed. Owner is investigating the repair and re-establishment of the lift-off tendon measurements.

The owner retained Morrison Knudsen (MK) as a consultant to evaluate the damage, instrumentation data, and geologic conditions of the dam. In addition, MK will design the necessary repairs. The reservoir level will be maintained at Elevation 1884 (about 5/8 H) or lower. Instrumentation data from owner dated 02/17/94 pertaining to piezometers, extensometers, joint movement, and survey monument movement received on 02/22/94. Piezometric level of piezometer 69-3 on left abutment increased about 12 feet after earthquake. Owner's geologic report dated 03/24/94 indicates intercommunication through horizontal lift joint at elevation 1978 between joints 10 and 11. MK's initial assessment report was submitted on 05/6/94. Division's letter dated 06/1/94 agrees with scope of interim remedial measures recommended by MK. Interim repairs to be completed by 12/94. Additional field investigation and structural analyses by MK are planned to determine appropriate permanent


Photo 7. Earthquake damage to the spillway chute, Pacoima Dam.

repairs at the dam. Preliminary drilling to assess the extent of the damage at the arch and left abutment has been completed. LACDPW's final geologic exploration report, Progress Report No. 2, was submitted on June 17, 1994. Pressure testing results indicate communication at the following construction joints: arch panel 5-6 at Elev. 1984; arch panel 8-9 at Elev. 1999; arch panel 9-10 at Elev. 1989; arch panel 10-11 at Elev. 1978. Max. water take at left abutment foundation equaled 17.7 gpm, 75 ft below crest at hole 94-2.

Owner plans to have cracks on dam, left abutment rock, and spillway tunnel grouted as part of interim repairs. In addition, open joint number 11 and horizontal lift joints at dam with observed communication will also be grouted and sealed. Confirmation water pressure testing and concrete coring will be accomplished after grouting is complete. Stability of left abutment rock and diagonal cracks on dam will be reevaluate by MK. Additional seismic movement instrumentation across crest joints has been recommended. Repair application and plans for interim repairs were received 09/2/94. Interim repair construction is currently underway (9/94).

Reservoir No. 5 Dam, Los Angeles County, Burbank

Height: 36 feet	Reservoir Capacity: 77 AF
Year Built: 1949	Storage during EQ: Unknown
Owner: City of Burbank	Dam Type: Reinforced tank
Epicentral Distance: 11.9 miles	Dam No. 4-7

A 1 gpm leak was observed between the reservoir wall and the gallery wall. The flow was clear. Instrumentation data submitted on 03/24/94 and 04/26/94. Piezometers remain dry and seepage at drain boxes essentially normal, although increases at South drain box #1 and North drain box #2 were observed. Owner has reported seepage at reservoir wall construction joint appears unchanged and continues to monitor.

The interior of the reservoir was examined by divers on 04/6/94. Cracking found on the concrete floor of the reservoir. Owner's survey data submitted on 04/26/94 indicates negligible post-earthquake movement. Montgomery Watson's, owner's engineer, report dated June 14, 1994 received on June 24, 1994. The report recommends repair of observed cracking, 1/8-inch maximum wide cracks, at northwest and southwest corners of reservoir concrete floor and a structural analysis of reservoir based on current state-of-the-art analysis. Most cracking was minor. Total seepage increased from about 9.2 gpm on 12/27/93 to about 40 gpm on 04/27/94. Majority of seepage increase occurred after 03/20/94 M5.3 aftershock. Grouting repair of reservoir concrete floor cracks was completed 08/25/94.

Sycamore Canyon Dam, Ventura County, near Simi Valley

Height: 40 feet	Reservoir Capacity: 890 AF
Year Built: 1981	Storage during EQ: empty
Owner: Ventura County FCD	Dam Type: Earth
Epicentral Distance: 15.0 miles	Dam No. 86-6

Transverse crack 1 to 2 millimeters (mm) wide and a few inches deep was found on right abutment. This crack ran across the crest and 1/3 of the way down the downstream slope and 1/2 of the way down the upstream slope of the dam. The crack was above an existing 12-inch diameter buried sewer pipe.

A follow-up inspection was conducted on February 1, 1994 and it was determined that the observed cracking was minor and no further work was required.

Santa Felicia Dam, Ventura County, near Piru

Height: 213 feet	Reservoir Capacity: 100,000 AF
Year Built: 1955	Storage during EQ: Elev.1015
Owner: United Water Cons Dist.	Dam Type: Earth
Epicentral Distance: 20.7 miles	Dam No. 1005

Minor hairline transverse crack across crest of dam near left abutment contact.

Surveys to assess movement at the dam were received on 03/2/94. Survey results indicate 3/4-inch maximum settlement near center of dam. Piezometer levels normal. Owner investigated 1/16-inch maximum crack at left end of dam. Crack has been determined to be minor and not a problem to dam. No further work required.

Rubio Debris Basin Dam, Los Angeles County, near Pasadena

Height: 64 feet	Reservoir Capacity: 37 AF
Year Built: 1944	Storage during EQ: empty Owner:
Owner: LA County, DPW	Dam Type: Earth
Epicentral Distance: 24.2 miles	Dam No. 32-21

Minor transverse hairline cracks found on the crest. Minor transverse and longitudinal hairline cracks about one-foot long were also observed a few feet from the right spillway wall. Concrete spalling inside the outlet tower at one corner exposing some rebar. Repair of localized damage to outlet tower was completed during 09/94. No further work required.

Morris S. Jones Dam, Los Angeles County, Pasadena

Height: 49 feet	Reservoir Capacity: 154 AF
Year Built: 1952	Storage during EQ: Unknown
Owner: City of Pasadena DW&P	Dam Type: Earth
Epicentral Distance: 26.7 miles	Dam No. 19-3

Spalling was observed at the concrete roof joints along with cracking of the earthfill on top of the reservoir.

The reservoir roof design was reviewed and it was concluded that the observed minor damage was no threat to the safety of the dam. Owner plans to repair localized concrete spalled areas and have the survey monuments on the dam measured. Survey has been completed by owner and is to be submitted to the Division for review. No further work required.

Cogswell Dam, Los Angeles County, north of Azusa

Height: 266 feet	Reservoir Capacity: 8,969 AF
Year Built: 1935	Storage during EQ: 1,247 AF
Owner: LA County, DPW	Dam Type: Rockfill
Epicentral Distance: 32.7 miles	Dam No. 32-5

Reservoir water level was at Elevation 1295, 90 feet below the spillway crest, during the earthquake. A new 1/8 to 3/16-inch wide transverse crack was found in the asphalt concrete near the right abutment contact at the crest of the dam. Crack judged surficial. The crack began at a buried pipeline and continued for 50 feet. Spalling was observed on the parapet wall adjacent to the observed crack. The parapet wall at this location tilted 1-inch upstream.

Owner repaired parapet wall, asphalt concrete cracks, and sealed parapet wall expansion joint during 9/94. A post-earthquake survey of the monuments on dam was received 10/17/94 and is being evaluated.

CONCLUSIONS

Overall, State jurisdictional dams within 47 miles of the earthquake epicenter performed well. Dams that did suffer significant damage, i.e. Pacoima, Upper and Lower San Fernando, and Porter Estate Dams, are either currently being or have been repaired to ensure there is no immediate threat to life and property. In addition, further instrumentation data reviews, investigations, and repairs are planned to ensure the satisfactory performance and safety of these dams.

Ranous, R., 1995, Damage to buildings from the Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 195-201.

DAMAGE TO BUILDINGS FROM THE NORTHRIDGE EARTHQUAKE

by

Richard Ranous[1]

DISCUSSION OF BUILDING DAMAGE

A key indicator to the severity of an earthquake is its impact on our building stock. The Northridge earthquake was no different in this respect. Looking at the results of the safety assessment process can give us an excellent indication of the amount of damage to buildings from an earthquake.

For Northridge, the safety assessment process began on the afternoon of January 17, 1994 and was finally completed in mid July. An all out effort was implemented in the first two weeks to evaluate and post as many buildings as possible. To accomplish this, the impacted jurisdictions within the three counties used all of their available staff supplemented by private sector engineers, architects and building inspectors from throughout the state, as well as building inspectors from other jurisdictions in California, provided by the Office of Emergency Services (OES) through the State's mutual aid program. Over this two week period, OES provided mutual aid assistance to seven jurisdictions and one state agency with approximately 600 individuals from its Safety Assessment Volunteer Program and 280 engineers from the U.S. Army Corps of Engineers. After the first two weeks most jurisdictions had completed their safety assessments thereby eliminating the need for additional personnel. During this two week period, in excess of 67,000 buildings had been inspected and by mid-July, when the final information had been provided to OES, a total of 113,915 buildings had been inspected, excluding schools and hospitals (Figure 1).

The following table represents the numerical results of the safety assessment process of all the evaluated buildings (Figure 1). It should be pointed out that most jurisdictions elected to perform only rapid evaluations. In a small number of cases detailed evaluations were performed. Under rapid evaluations, the construction material and lateral force resisting systems are not recorded, therefore, the only information that is common between the rapid and detailed evaluation is the posting and the occupancy. Consequently, specific information and comparisons must be limited to these two common pieces of information.

[1] Office of Emergency Services, Southern California Earthquake Preparedness Project, Pasadena, California.

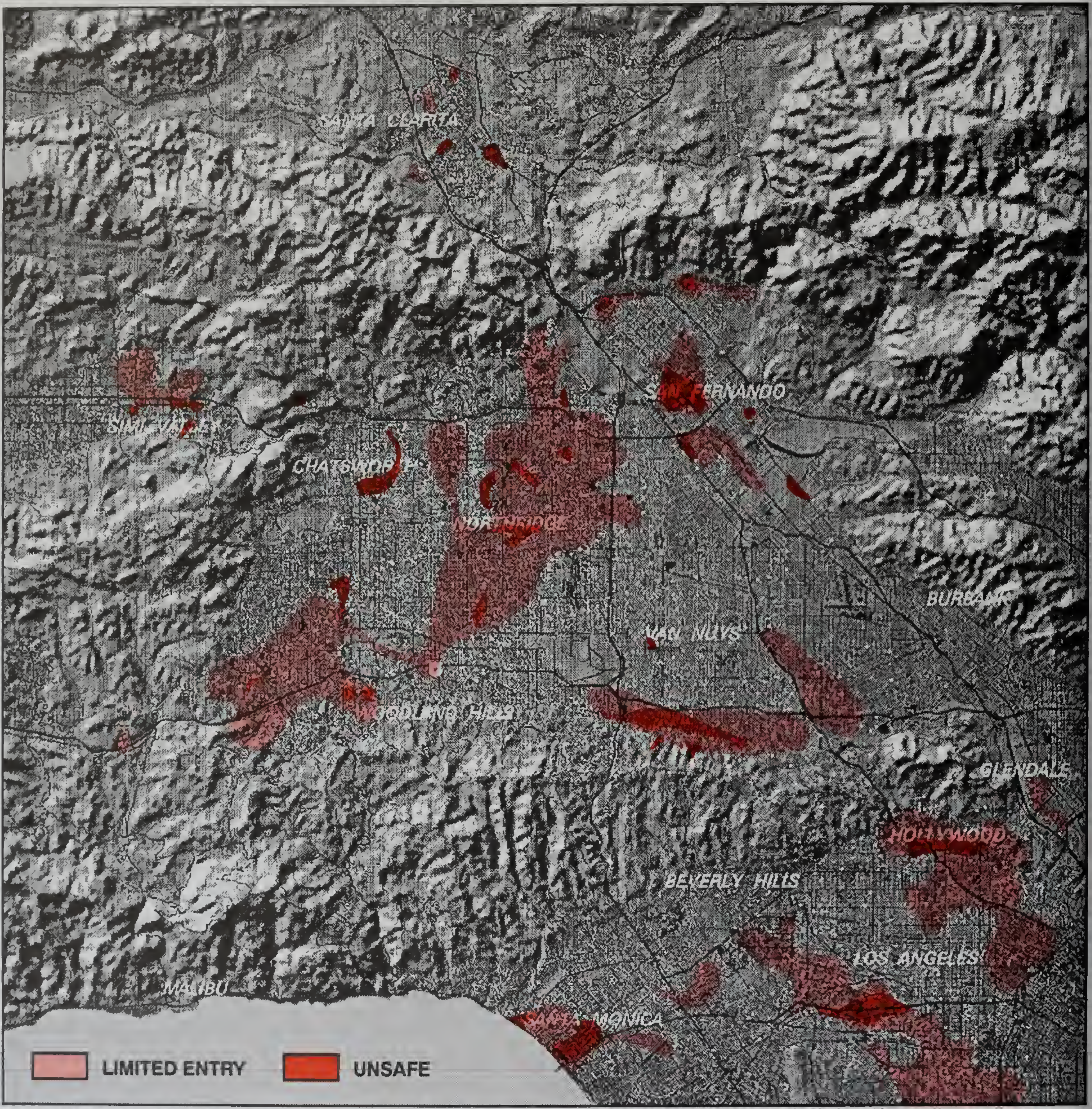


Figure 1. Building and Safety Damage Assessment from the January 17, 1994 Northridge earthquake, showing the area where a total of 113,195 buildings (excluding schools and hospitals) were inspected and posted as to occupancy categories. Red tags were placed on buildings unsafe to enter; yellow tags designated buildings with entry limited to authorized persons. Buildings with no restrictions on entry were designated by green tags. Modified from Building Inspection Disaster Map DR-1008, California Office of Emergency Services.

RESULTS OF THE SAFETY ASSESSMENT PROCESS

Analyzing this table allows us to see how buildings performed in the global sense. The occupancy categories are taken directly from the Applied Technology Council (ATC)-20 evaluation forms and the numbers represent "first-time" inspections. The "unknown" category represents those buildings which were reported to have been inspected but there was no indication of the posting that was used, if any. All jurisdictions were asked to provided the number of buildings inspected and the breakdown of the placards. The unknown category represents the difference in the number of buildings inspected and the total of the various placards. A large percentage of the buildings in this category probably fall in the INSPECTED category and were simply not posted. This has been a fairly common occurrence in past earthquakes.

Looking at the "percent of overall total" at the bottom of the table gives us a general indication of how well our buildings performed. Of the 113,915 buildings assessed, only 13% (14,481 buildings) sustained a level of damage which would not allow their continued, full-time occupancy. Only 3% (2,998 buildings) were damaged to a level where they were considered to be a significant threat to life-safety (UNSAFE).

Table 1. Safety assessment of buildings (schools and hospitals excluded) in the area affected by the Northridge earthquake, January 17, 1994 – mid July, 1994.

OCCUPANCY	RED[1] UNSAFE	YELLOW[2] LIMITED ENTRY *	GREEN[3] INSPECTED	UNKNOWN	TOTAL FOR OCCUPANCY
Residential (Dwelling)	2109	9204	80867	5032	**97212**
% of Occupancy Total	2%	9%	83%	5%	**85.3%**
Other Residential	9	24	304	177	**514**
% of Occupancy Total	2%	5%	59%	34%	**0.5%**
Commercial	583	1267	5436	242	**7528**
% of Occupancy Total	8%	17%	72%	3%	**6.6%**
Industrial	54	173	759	1878	**2864**
% of Occupancy Total	2%	6%	27%	66%	**2.5%**
Office	4	8	90	9	**112**
% of Occupancy Total	4%	9%	80%	8%	**0.1%**
Assembly	3	6	16	5	**30**
% of Occupancy Total	10%	20%	53%	17%	
Emergency Services	4	1	14	10	**26**
% of Occupancy Total	4%	4%	54%	38%	
Governmental/Public	0	6	34	32	**72**
% of Occupancy Total	0%	8%	47%	44%	
Worship	7	8	67	8	**65**
% of Occupancy Total	8%	9%	74%	9%	
Mixed Use	10	20	31	4	**65**
% of Occupancy Total	15%	31%	48%	6%	
Other	218	765	2693	1726	**5402**
% of Occupancy Total	4%	14%	50%	32%	**4.7%**
TOTAL	**2998**	**11483**	**90311**	**9123**	**113915**
% of Overall Total	3%	**10%**	**79%**	**8%**	

*** New RESTRICTED USE category was not used except in some mobile home parks where OES provided placards for the evaluation teams.**

These totals do not include schools and hosptials.

[1] Red Tag: unsafe to enter

[2] Yellow tag: entry limited to authorized persons

[3] Green tag: no restrictions on entry/use

From the standpoint of performing safety assessment in a post-earthquake environment, this table shows us that the development of ATC-20 "Procedures for Postearthquake Safety Evaluation of Buildings," accomplished its intended purpose. ATC-20 was developed in order to help provide consistency in the evaluation of buildings. This document was ready for use just one month before the Loma Prieta earthquake. Since very few people were familiar with the document, it was not used exclusively during that response. The Humboldt and Landers earthquakes in 1992 were not sound tests of the document because of the relatively small number of buildings inspected and the small number of different occupancies impacted. The Northridge earthquake, on the other hand, provided the test we needed. Looking at the most important categories for consistency, we see that UNSAFE (Red) structures varied from about 2% to 4% of the total of that particular occupancy category. There were some anomalies in this area which, for the most part, can be attributed to the small number of buildings within that particular category. The LIMITED ENTRY (Yellow) had a little more variation in the totals but was still fairly consistent. This category varied from a low of 4% to a high of 31%. Again, some of this variation can be attributed to the small number of structures in a particular occupancy category. However, probably a more realistic answer was the confusion that has always been associated with the LIMITED ENTRY placard. Unfortunately, the new RESTRICTED USE placard, which replaces LIMITED ENTRY, was not yet widely distributed and did not get used during this response. Overall, we can say that the concerted effort of OES and the professional organizations, involved in the safety assessment process, to provide training in ATC-20 has paid off. We have achieved a level of consistency that is acceptable to local government which will only get better with more training and experience.

This table also tells us that the most heavily impacted occupancies where residential (Dwelling). This category includes single-family residences, apartments, and condominiums. The "other residential" category represents primarily hotels, motels and other similar occupancies. Of all the buildings inspected, 85.3% (97,212 buildings) were residential dwelling properties. The vast majority of these structures where light, wood-framed buildings. These percentages substantiate our long-held beliefs that light, wood-frame structures perform well. A total of 11% (11,313 structures) were posted as either UNSAFE or LIMITED ENTRY and a large percentage of these structures where multi-family buildings. This certainly explains why there was such a large need for emergency shelters and tents in the parks in the first week after the earthquake.

After residential occupancies, commercial and industrial occupancies represented the next largest categories with 6.6% and 2.5% of the total, respectively. The "other" category represents information provided to OES where the specific occupancy was not noted. In many cases, these were probably mixed occupancies and should have been included in the "mixed use" category. In other cases, they may represent occupancies that could have fallen into more than one category. The remaining categories each represent less than 1% of the total.

RESIDENTIAL BUILDINGS

Apartments and Single-family Residences

Most of the 11,313 residential structures rendered uninhabitable for long-term occupancy were light, wood-frame buildings and were multi-family buildings (apartments and condominiums). Many of the badly damaged apartment buildings were built with parking at, or below grade, under the buildings. To accommodate the parking, shear panels on one or more sides did not extend to a foundation. These panels terminated over moment frames or cantilevered columns thereby creating "soft stories." Ever since the San Fernando earthquake in 1971, we have recognized that soft stories significantly impact the ability of a structure to adequately resist ground motions. These buildings performed much as we would expect and resulted in full or partial collapses of the first stories thereby rendering the building not habitable.

A second issue that applied to both multi-family and single-family residences was the damage to portland cement plaster (stucco) used as shear panels to resist seismic ground motion. When tests were conducted on the shear resistance of stucco, the stucco itself was found to have fairly good shear resisting capability. This is why the building code allows its use in shear panels. The main problem comes in the installation of the material on the building. Investigations after the Northridge earthquake showed two common problems attributed to the installation of stucco where that material provided the only lateral force resistance in the building.

The first, and most significant, problem was in the nailing of the wire lath which reinforces the stucco. The lath was found to be connected by nails or staples only along the studs. Connections to the plates at the top and bottom of the walls only occurred at the location of the studs. The wire lath is not only the reinforcing for the stucco. It is the material that gets connected to the studs and plates and, therefore, provides the shear transfer from the wall to the foundation. It is also through the connection of the lath that the lateral forces from the roof and floors is transferred and accumulated in the stucco.

The nailing of the lath is the only connection available to accomplish this transfer. When the nailed connections are only spaced 16 inches center to center, the shear forces can not be adequately transferred and there is excessive movement of the wall which, in turn, severely cracks the stucco or results in the building moving relative to its foundation.

The second problem found with stucco was the lack of proper embedment of the lath within the stucco. This embedment is what allows the stucco to transfer the shear forces to the lath which in turn distributes the forces through the connections to the foundation. In many cases, lath was found to have been stapled to the studs in such a way that the lath was in contact with the stud resulting in no embedment in the stucco. Using staples is not a violation of the code. They can be used as long as there is at least a 1/4-inch embedment of the lath in the stucco. To accomplish this, one must use a "spacer" or "ties" to hold the lath off the surface of the stud before the stucco is applied. Since this did not happen, there was little or no embedment of the lath in the stucco at those areas where the force transfer was most critical.

Another reason for damage to single-family residences was the lack of sill bolting and adequate bracing of cripple walls in older homes. This has been a major cause of damage to homes in past earthquakes and was a significant cause of damage as a result of the Northridge earthquake. A number of hillside homes also suffered significant levels of damage because of inadequate bracing of cripple walls. Generally speaking, this damage was a result of tall cripple walls, utilized because of the sloping site, with little or no bracing. Where bracing was found, the panels were narrow with respect to their height resulting in large overturning forces.

COMMERCIAL BUILDINGS

From the safety assessment table, we see that the second largest occupancy category evaluated was commercial structures. The total number of these structures represented 6.6% of the total buildings inspected; however, this category represents the largest anomaly. Comparing the percentages of red and yellow placards to the total for the occupancy we see that 26% of the structures received enough damage to render them unsafe or to restrict their occupancy. This can probably be attributed to three prevalent factors. First, there were a large number of parking structures which suffered significant levels of damage and the best occupancy category for these structures would have been commercial. Second, many of the damaged unreinforced masonry buildings fell into the commercial category. Finally, there was a large amount of nonstructural damage suffered by commercial structures which could have resulted in the UNSAFE and LIMITED ENTRY placards because of the significant falling hazards present, potential asbestos contamination, as well as equipment damage which presented a hazard to the occupants. At this time we do not have information as to specific structural problems related to these buildings beyond what has currently been identified.

During the first few weeks after the Northridge earthquake, it appeared that one of the big issues, in relation to damage, was going to center on parking structures. Many communities had concrete parking structures which where severely damaged and in many cases experienced partial or full collapses. Later, this issue was overshadowed by the problems found with steel moment frame buildings.

For the most part, the damage in parking structures was a result of the lack of ductility in the interior columns which where not a part of the lateral-force resisting system. These columns are not designed for the direct shear forces, and associated bending, resulting from seismic ground motion. However, to account for the displacement these columns are subjected to by the movement of the structure as a whole, the code requires them to be designed for a minimum displacement. The code defines a level of movement that is based on the response characteristics of the lateral-force resisting system. During the Northridge earthquake, these structures experienced displacements (drifts) which were larger than the code anticipated. Consequently, those columns lacked the confinement reinforcing which provides the ductility necessary to resist forces into the inelastic range. The result was failure of these columns which, in some cases, resulted in the partial collapse of interior bays of the structure.

Some of the parking structures damaged used precast concrete, long-span double tee elements. This system is usually used with cast-in-place concrete supporting elements for both the vertical and lateral force resisting systems. Under this system, "shelves or seats" are used to provide the vertical support for the double tees. Diaphragms are formed by either interconnecting the flanges of the double tees by welding embedded plates together, or by pouring a thin topping slab. The tees are usually connected to their vertical supports at one end only by field welding the steel bearing plate in the tee to a steel bearing plate cast in the supporting member. This is done to allow the tee to expand and contract with the temperature differentials experienced on a day-to-day basis. Welding both ends of the tee would not allow for this movement and, in turn, would result in cracking the tee at its support. It appears that the failures in this particular type of system were a result of differential movement of the various parts of lateral force system. This movement

pulled the supporting "shelves" out from under the tees at the unwelded ends causing them to fall which, in turn, broke the connections at the connected ends.

As in many past earthquakes, unreinforced masonry buildings added to the rolls of unusable buildings. The City of Los Angeles had essentially completed its retrofit program and, as a whole, these retrofitted structures performed as expected. With a few exceptions they did not fully collapse and there was no apparent loss of life attributed to unreinforced masonry. Again, generally speaking, the damage in these buildings occurred primarily at building corners. In those communities where retrofit programs had not been completed, the damage to unreinforced masonry was identical to what we have seen after other earthquakes. That is, partial collapses attributed to lack of connections between the diaphragms and the walls, parapet failures, and in-plane shear failures in the walls.

Certainly, the Northridge earthquake reinforced the need for proper mitigation of nonstructural elements within buildings. In many cases, otherwise undamaged buildings were rendered uninhabitable because of damage to the nonstructural systems. Probably the most prevalent form of nonstructural damage was broken storefront windows, followed by collapse or partial collapse of suspended ceilings. Another area of nonstructural damaged that reduced the ability of commercial buildings to reopen were damaged electrical systems. In one case, a damaged building was lost to fire when the power was restored; the building's electrical distribution system was damaged causing the fire to start.

INDUSTRIAL BUILDINGS

Industrial occupancies represented 2.5% (2,864) of the total buildings evaluated. Of these, only 8% (227) were rendered uninhabitable for long-term occupancy after the earthquake. The majority, 66% (1,878), of this occupancy category fell into the UNKNOWN category. Again, a large percentage of these were probably in the INSPECTED category and were not posted because the jurisdictions elected not to post green placards.

The majority of the 2% of this occupancy category which where posted as UNSAFE were probably pre-1973 tilt-up structures. According to reports from engineers and investigating committees, these buildings suffered much the same type of damage as the tilt-up buildings that were damaged by the 1971 San Fernando earthquake. In particular, the UNSAFE placards were a result of failures of the anchorage connections of the panels to the roof diaphragms. This left tilt-up panels with no lateral support and subject to outward collapse unless they were braced. Such a collapse would also lead to a partial collapse of the roof structure. Because most industrial, tilt-up buildings use panelized roof construction, these potential collapses would not be limited solely to what would be classified as a bearing wall. Panelized roof systems use all walls for some measure of vertical support for the roof.

MOBILE HOMES

Mobile homes are not represented in the table of results of the safety assessment process. The majority of mobile homes are under the jurisdiction of the Department of Housing and Community Development (HCD). Because of the small number of available staff in southern California, mobile homes where not inspected on a widespread basis and, therefore, are not included in the results.

As with many past earthquakes, mobile homes where damaged primarily by being "knocked" off their jack stands as a result of the ground motions. In many cases, this resulted in damage to water heaters which, in turn, caused fires which destroyed the unit. In the weeks after the earthquake, OES was able to determined that more than 5,000 mobile homes had been damaged in approximately 120 mobile home parks within the three counties. Repairs to the structures were slow in being performed because owners did not understand the required permitting process nor the inspection requirements that were required to be enforced by California standards. Most people felt that all they needed to do was have their units placed back on their supports. Consequently, work was done simply to restore them on their support systems but the units were still uninhabitable because other elements were damaged or substandard. This level of work simply restored the units to their "pre-disaster" condition and no attempts were made to mitigate the damage.

The majority of these homes where owned by low- or fixed-income families who did not have the resources to purchase and install earthquake resistant bracing systems. The damaged units, where there was no insurance or inadequate insurance coverage, were eligible for federal assistance under FEMA's Minimal Home Repair program. Basically, this program provided sufficient funds to restore the mobile homes back on their support systems. At this point, OES became involved and worked with FEMA to implement a hazard mitigation approach which was eligible under federal regulations. It was agreed that in addition to their repair money, those who were eligible for the Minimal Home Repair program would also received funds to purchase and install earthquake resistant bracing systems.

To facilitate this work, OES took on the task of coordinating the repair and mitigation work in close cooperation with HCD. Under this program, OES hired O'Brien-Kritzberg as the management team and Bailey

Construction as the general contractor. Those homeowners who were eligible for the Minimal Home Repair program could choose to work with the OES team or hire their own contractors. Under the OES program, the O'Brien-Kritzberg management team organized the parks and worked with the owners to identify the scope of work at each unit. Bailey Construction then would put the entire park out to general bid to select a single contractor to work on those units within the park for those who joined the OES program. Bailey Construction also provided the construction supervision necessary to make sure that certificates of occupancy could be issued by HCD. The program was opened to those individuals who did not want, or did not have the ability, to take the time necessary to find contractors on their own. Overall funding of the work was not dependent on who performed the work. Those individuals who were eligible for the Minimal Home Repair Program and elected to find their own contractors were provided the repair funds as well as the funds to purchase and install earthquake resistant bracing from FEMA.

To more fully address all the issues involved with the damage resulting from the Northridge earthquake, Governor Pete Wilson, by executive order, has instructed the Seismic Safety Commission to review the State's practices relating to seismic safety.

Bellet, D., and Mujumdar, V., 1995, Northridge earthquake, damage to public school buildings *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 203-208.

NORTHRIDGE EARTHQUAKE DAMAGE TO PUBLIC SCHOOL BUILDINGS

by

Dennis Bellet[1] and Vilas Mujumdar[1]

SUMMARY

This report (adapted from Bellet and Mujumdar, 1994) provides a detailed review of successes and failures in the design and construction of public school buildings that were located in the region near the epicenter of the January 17, 1994 Northridge earthquake. Emphasis is on typical damage observed in this earthquake and recommendations for mitigation. The damage observed can be grouped into four major categories: (1) pole supported structures, (2) buildings constructed before 1974, (3) portable buildings, and (4) nonstructural components.

The Office of Regulation Services (ORS) within the Division of the State Architect is an enforcement entity with responsibilities for the plan and construction review of state-owned and state-leased essential service buildings, public school buildings (K-12), and community college buildings.

The Office consists of three units: (1) Access Compliance, (2) Fire and Life Safety, and (3) Structural Safety. Structural Safety review was established by legislation in the Field Act, passed in 1933 after the Long Beach earthquake. The Field Act requires an independent state agency to review the plans and supervise the construction of public school buildings with the goal as stated in the regulations that: "School buildings constructed pursuant to these regulations are expected to resist earthquake forces generated by major earthquakes of the intensity and severity of the strongest experienced in California without catastrophic collapse, but may experience some repairable architectural or structural damage."

In the days and weeks following the Northridge earthquake ORS provided assistance to school districts in the post-earthquake safety evaluation of public school buildings for use as community shelters and for reoccupancy by students and teachers. At the request of the school districts over one hundred school campuses were evaluated by structural engineers working under the authority and guidance of ORS. No catastrophic collapses of any public school buildings were reported; thus, the goals of the regulations and the Field Act were achieved. However, this success must be tempered with the knowledge that, had the earthquake occurred during school hours, hundreds of students probably would have been seriously injured from hazards associated with nonstructural components.

Recommendations for code changes, legislation, and school district action are provided in this report. If implemented these changes would significantly reduce the life safety hazards associated with existing public school buildings that were designed and constructed to outdated codes and regulations.

[1]California Department of General Services, Division of the State Architect, Office of Regulation Services, Sacramento, California

SEISMOLOGICAL AND GEOTECHNICAL ASPECTS

As reported by the Earthquake Engineering Research Institute,approximately 22 magnitude 4 and 2 magnitude 5 or greater earthquakes were recorded in the three weeks following the main event. Aftershocks above magnitude 4 are expected to occur in the area over the next year. Information provided by the Department of Conservation, Division of Mines and Geology, Strong Motion Instrumentation Program indicates that the strongest shaking recorded by free-field instruments was in the North-South direction and had maximum horizontal accelerations of between 0.25 and 0.50 g. The Olive View Hospital station in Sylmar, the Tarzana station, the Pacoima Dam station and the Santa Monica City Hall station all provided records with horizontal maximum accelerations from 0.91 to over 2.00 g which significantly exceeded the recordings from other stations in the area. These stations also provided vertical acceleration records with maximum accelerations exceeding 0.60 g in several cases.

Numerous surface disruptions caused by the Northridge earthquake have been identified and documented; however, no agreed upon primary surface faulting has been identified. Surface disruptions included buckled curbs and sidewalks, fissured concrete and asphalt, ruptures of subsurface utility lines, and some minor left-lateral displacement.

Van Gogh Elementary School in Granada Hills, just north of the epicenter, had some building damage due to ground cracking. One crack in the ground, less than one inch wide, passes directly through the entire wood-framed main school building coincident, in at least one location, with a change in the elevation of the floor slab. The crack is reflected in the slab-on-grade and at the base of the walls, but wall cracking appeared to close as it progressed up toward the roof.

Numerous ground cracks were also observed at Kennedy High School in Northridge. One such crack damaged the concrete masonry wall of a gymnasium.

A geotechnical hazard report is required for all school construction that falls within an Alquist-Priolo special studies zone. School buildings are not allowed to be constructed on or within 50 feet of an active fault trace. The damage to school buildings due to the ground cracking caused by the Northridge earthquake did not appear to be a life safety threat and would not have been predicted by extensive geotechnical investigations. However, the threat to life safety associated with known geotechnical hazards such as primary fault displacements, liquefaction, landslides, and, more recently, with shattered ridges, requires that the advice of experts in this field must be procured and followed whenever there is concern that such a hazard exists. The level of geotechnical investigation currently required for California public school building projects appears to be appropriate and changes in the regulations are not anticipated.

POST–EARTHQUAKE SAFETY EVALUATIONS

Office of Emergency Services (OES) volunteer engineers, Division of the State Architect, Office of Design Services (DSA/ODS) engineers and ORS engineers surveyed 127 school campuses for 45 school districts using Applied Technology Council (ATC-20) Rapid Evaluation procedures. Of the structures surveyed, 24 were rated unsafe (red tag); 82 were rated limited entry (yellow tag); all remaining buildings were rated inspected (green tag). ATC-20 procedures indicate the following conditions should exist for the following ratings:

- Unsafe (red). Extreme hazard, may collapse. Imminent danger of collapse from an aftershock. Unsafe for occupancy or entry.
- Limited entry (yellow). Dangerous condition believed to be present. Entry by owner permitted only for emergency purposes and only at own risk. No usage on continuous basis. Entry by public not permitted. Possible major aftershock hazard. (These structures generally will receive a more detailed evaluation.)
- Inspected (green). No apparent hazard found, although repairs may be required. Original lateral load capacity has not significantly decreased. No restriction on use or occupancy.

A review of the reports and on site evaluations indicate that the engineers rated many structures very conservatively. With the exception of the portable buildings and some of the lunch shelters, most structures rated "unsafe" were not in a reasonable danger of collapse. Many buildings were rated "limited entry" whenever any possibility of structural damage was suggested or if nonstructural hazards were apparent. ATC-20 procedures are intended to rate the entire building. Nonstructural hazards are considered to be localized hazards that warrant an "area unsafe" rating. Errors on the conservative side are appropriate when rating school buildings following severe earthquakes. However, recovery from major earthquakes for communities is improved when schools become operational in a timely manner. Overly conservative rating of schools can hinder reoccupancy and slow community recovery. Additional training, post-earthquake and pre-evaluation briefings and daily debriefings are recommended for engineers that perform school building damage and safety assessment evaluations.

ORS does not have authority to post public school buildings and acts only in an advisory capacity to school districts. Posting of buildings is expected by the public and when the expected placard is not in place, leads to confusion and distrust . School districts do not have the resources to provide this service. ORS should be given the authority to post public school buildings within its jurisdiction following moderate and major earthquakes. With posting authority comes the responsibility to respond to the school district's needs to upgrade the posting placards as the schools mitigate or remove the hazards that warrant other than inspected (green) posting placards. This authority would require legislation.

POLE-SUPPORTED STRUCTURES (COVERED WALKWAYS, LUNCH SHELTERS, AND CANOPIES)

These structures generally consist of a flat roof supported by steel posts embedded into concrete footings. Covered walkways can be several hundred feet long and intersect with buildings and other covered walkways in numerous places. The steel posts and concrete columns resist lateral loads by bending. These types of structures will sway more than most other structures when subjected to cyclical seismic forces. The connections of the wood roof framing members to the steel columns are exposed to the weather and can suffer deterioration due to dry rot.

Several of these walkways, shelters, and canopies exhibited damage either at the beam/column connection or at intersection with other buildings or other walkways. Damage generally consisted of: (1) wood beams slipping off of beam seats due to connection failures aggravated by dry rot conditions, (2) damage that loosened connections due to pounding of one structure against another, (3) spalling of concrete at the top of columns, and (4) minor racking of the structures.

Current regulations recognize the larger displacements and amplified accelerations that these types of structures must endure. No changes to the regulations are anticipated. However, since much of the damage occurred as a result of poor maintenance, ORS should advise school districts of problems that may occur if corrective action is not taken.

PERMANENT BUILDINGS CONSTRUCTED BEFORE 1974

A few permanent school buildings suffered structural damage in this earthquake. No detectable structural damage resulted in the collapse or partial collapse of a building nor did a structural member fall to the floor. Spalling of small pieces of concrete or masonry did occur at very localized areas, generally on the outside of a building. These pieces of concrete or masonry would have been injurious to anyone positioned directly below the location of the spall.

The structural damage to permanent buildings reported for this earthquake is not easily categorized to a specific structural system. Additionally, only a few permanent buildings suffered structural damage, which limits any generalizations. Horizontal roof diagonal bracing rods buckled, shear walls showed diagonal cracking, spalling occurred at concrete beam/column joints, and ground cracks caused similar cracks in the building. Repairable structural damage to a few buildings is expected when a large inventory of buildings are subjected to an earthquake of this magnitude. Most structural damage was to buildings constructed to pre-1974 building regulations.

A listing of the hazardous older school buildings, such as non-ductile concrete frame and pre-1974 concrete tilt-up wall structures, has not been established due to lack of funds to complete the investigation and anticipated expensive rehabilitation, demolition, or replacement of these structures. The school staff, parents of pupils, and the community have a right to know that some school buildings that were designed and constructed to outdated codes are hazardous. The Berkeley City Unified School District evaluated their buildings and were informed that a few

Photo 1. Acoustical ceiling failure at John F. Kennedy High School in Northridge, California. Photo by David Ring, Office of Regulation Services.

of their structures were hazardous. The Berkeley community successfully provided funding to mitigate the problem.

PORTABLE BUILDINGS

Several larger, older portable buildings were supported on 2 to 3 foot tall wood framed cripple walls in the area affected by significant ground shaking from the Northridge earthquake. Current regulations require a permanent foundation for all portable buildings with cripple walls over 18 inches in height. The wood foundation for these older portable buildings in some cases suffered from dry rot and a subsequent loosening of the nails and weakening of the foundation intended to resist the seismic loads. The foundations constructed before 1974 are also designed to loads 25 percent less than current requirements. Although these foundations did fail by cripple wall racking up to 8 inches out of plumb, complete collapse did not occur.

Several nonconforming portable school buildings without lateral load resisting foundation systems fell off their supports and in some instances the jackstands penetrated the flooring. Additionally, many temporary nonconforming portable buildings were placed on campuses as earthquake damage was being repaired on the existing buildings. Aftershocks in some cases also displaced support systems for these buildings. ORS is developing processes and procedures to improve the seismic performance of (1) temporary, (2) existing nonconforming, and (3) long term relocatable school buildings. The focus of the processes and procedures is to provide safe structures to school districts in a timely manner to meet their housing needs at a low cost. This will discourage school districts from using nonconforming buildings and encourage them to eliminate existing nonconforming buildings.

NONSTRUCTURAL HAZARDS

Damage to nonstructural elements in public school buildings due to the ground motions generated by the Northridge earthquake has provided no significant new information as to problems school districts will face in the repair and cleanup following earthquakes of this magnitude. The published methods for mitigating nonstructural hazards were effective in resisting the forces from this earthquake. It appears that many southern California school districts are mitigating the nonstructural earthquake hazard problem, yet a majority of the school districts have done little if anything before this earthquake. Similar to other recent earthquakes, excepting the library damaged by the Coalinga earthquake, little glass damage was observed or reported, even in schools with large north-facing glazing that was a common architectural trend in the 1950s and 1960s. The types of elements damaged in previous earthquakes were once again damaged in this event. These damaged elements can be grouped into three main categories: (1) ceilings and light fixtures, (2) contents damage, and (3) unanchored utilities equipment and unbraced pipelines.

Ceilings and Light Fixtures

Suspended ceiling systems that were installed before the lessons learned from the 1971 San Fernando earthquake were the most common nonstructural element damaged. Typically these ceiling systems do not have lateral splay wires, compression struts, or adequate connections between members, all of which have been corrected in the regulations following the San Fernando earthquake. Young children can be severely traumatized even when only the lightweight ceiling panels fall because they perceive their school environment to be unsafe. This trauma can cause learning disabilities that may harm a child's future education compared to pupils who were not exposed to the trauma of falling ceiling tiles during an earthquake.

Photo 2. Pendant light fixture failure at Northridge Junior High School, Northridge, California. Photos by Gary McGavin, Seismic Safety Commission, except as noted.

Present efforts to insure that current code complying designs are constructed and inspected on California public school campuses has remedied the danger of falling ceiling panels even when subjected to large shaking intensities. The Office of Regulation Services (ORS) does not anticipate significant changes in the regulations regarding suspended acoustical ceiling systems.

The surface and recess mounted light fixtures generally did not fall to the floor, yet the light fixture lenses and florescent light bulbs did fall. The hazard associated with hanging grid members, fallen lenses, and bulbs is aggravated as power failure is likely and evacuation may sometimes be required through dimly lit or dark hallways. Photo 1 shows the failure of the suspended acoustical ceiling system in the corridor of the administration building at John F. Kennedy High School in Northridge. This building was approved for construction in December of 1970 before the regulations required lateral bracing wires and separate hanger wires for light fixtures.

Many pendant mounted light fixtures fell to the floor due to the failure of the ball and socket joint or the stem. The wire nut that connects the light fixture wiring to the main wiring does not resist the gravity forces acting on the pendant light fixtures. This defect has been corrected in the regulations for public schools by the additional requirement for a safety wire connecting the fixture directly to a structural member. However, thousands of light fixtures were installed before this regulation was added to the code. Had the Northridge earthquake occurred with students at their desks, injuries could only have been avoided if the required "duck, cover, and hold" training produced real event action. Approximately 100 classrooms had one or more light fixtures fall to the floor or on top of desks. Photo 2 shows the failure of pendant mounted light fixtures in one of several classrooms at Northridge Junior High School. These classrooms were constructed in 1960, before the lessons learned from the San Fernando earthquake revealed the need for separate safety wires connecting the fixture to the structure above. These fixtures can weigh up to 80 pounds and have metal parts with relatively sharp edges that could cause serious injuries to pupils in the wrong place at the wrong time. This nonstructural hazard probably provides the greatest possibility of injuring students and teachers in the event of an earthquake during school hours.

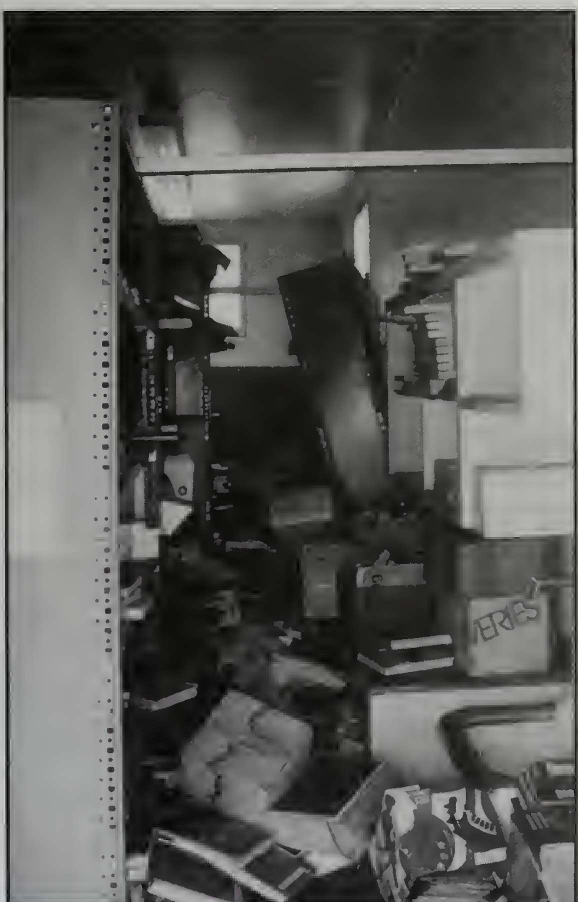


Photo 3. Note conditions at braced shelf (left) compared to unbraced shelves (right).

Contents Damage

Public school Districts that actively pursue efforts to anchor and brace bookshelves, library shelving, file cabinets, televisions, aquariums, and other objects that would fall or topple during strong ground shaking found that the costs for clean-up were significantly lower than the cost for districts that were unprepared for the inevitable earthquake.

Plaster walls and ceilings, especially those made with wood lath instead of the more modern wire mesh, suffered extensive damage in areas that were intensely shaken. Plaster ceilings in auditoriums are especially hazardous in that the heavy plaster that falls from these higher ceilings can cause more severe injuries.

Photo 3 demonstrates the successful bracing of shelving in the foreground (left side of the photo) and the failure to anchor one side of the shelving in the background (right side of the photo). This is an example of the typical nuisance damage and cleanup for displaced contents of open shelving. If the earthquake had occurred 30 hours later, students and teachers would have been injured by these hazards that could have been mitigated at little or no cost.

Most of the contents damage can be labeled as a nuisance problem, yet when heavy items, hazardous chemicals or items with sharp edges or glass parts are unanchored or braced or stored on top of shelves they become a life safety threat. Additionally, when expensive

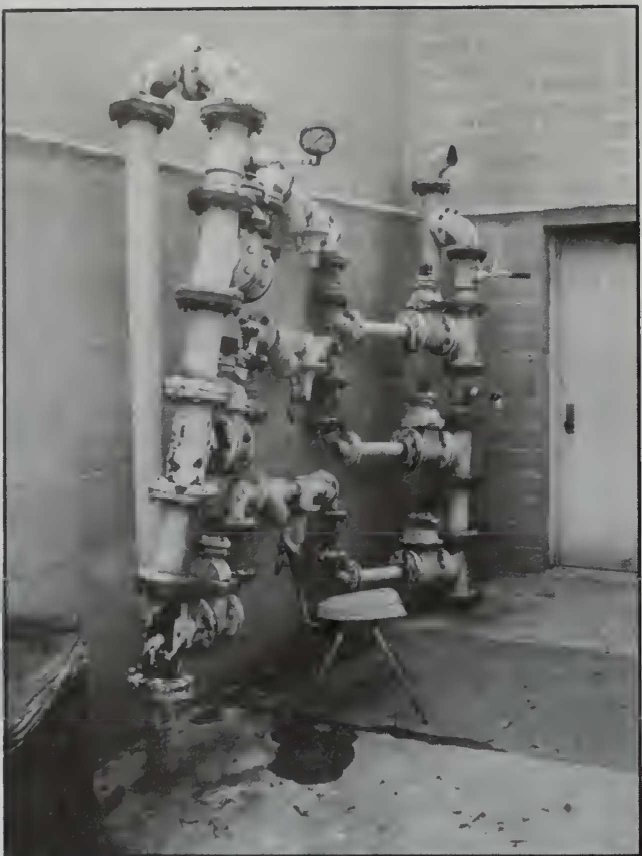


Photo 4. Earthquake damage to large utility piping in Kennedy High School.

Photo 5. Earthquake damage to small utility piping at Danube Elementary School.

items such as microscopes and electronic equipment are not anchored or properly stored their replacement can be very costly. Most of the schools in the area had anchored their computer equipment and had very little damage. However, this success may have been driven more in an effort to protect against theft rather than earthquakes. Future efforts to mitigate nonstructural hazards associated with contents should also list the corollary benefits such as access control of hazardous chemicals and theft prevention for expensive equipment.

Unanchored Utilities Equipment and Pipelines

Following the earthquake, water, gas and electrical power supplies controlled occupancy of a few school buildings that were structurally undamaged. Failure of fire suppression sprinkler lines also occurred in a few schools which resulted in costly damage and extensive cleanup effort. Small as well as large pipelines failed in the Northridge earthquake. Photo 4 shows large piping damaged at Kennedy High School. Photo 5 shows small water line damage at Danube Elementary School.

The regulations require that all equipment and piping be anchored and braced to resist the design seismic forces; however, only floor supported equipment weighing over 400 pounds and overhead equipment weighing over 20 pounds must be specified on the plans to be reviewed. Project specifications are required to indicate that piping is to be braced in accordance with nationally accepted standards. Observed and reported damage to equipment and pipelines indicates that if current anchoring and bracing requirements for public schools are followed damage will be minimal. ORS will review the results of studies or reports on anchoring and bracing of equipment and pipelines to determine if inspection procedures or code changes are needed.

REFERENCE

Bellet, Dennis and Mujumdar, Vilas, 1994, Northridge earthquake performance of public school buildings, Final Report: Division of State Architect, Office of Regulation Services, May, 12 p.

Pandya, S., 1995, Earthquake damage to hospitals *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 209-218.

EARTHQUAKE DAMAGE TO HOSPITALS

by

Sharad Pandya[1]

INTRODUCTION

The Northridge earthquake was the most significant event in California since the 1971 San Fernando earthquake to test the ability of hospitals and skilled nursing facilities (SNF) in southern California to withstand earthquake ground motion and provide medical services thereafter. The purpose of this report is to provide a brief overview of the damage sustained by these facilities during the earthquake.

Damage assessment surveys conducted by State of California, Office of Statewide Health Planning and Development (OSHPD) provide valuable information on the performance of primary structures and non-structural systems of both pre-Act and post-Act buildings. Pre-Act buildings are defined as hospital and SNF buildings approved for construction by local government building departments prior to March 7, 1973, the date when the Hospital Seismic Safety Act (Act) became law. Post-Act buildings are those buildings which were approved for construction by OSHPD or its predecessor, State government entities, after March 7, 1973. Post-Act hospital buildings are generally designed for earthquake forces at least 50% greater than that required for non-hospital buildings. Furthermore, the design and construction of post-act hospital buildings require independent review by OSHPD.

DAMAGE SURVEY

OSHPD surveyed damage at 472 health care facilities, each having one or more buildings, and posted the buildings with red (unsafe to enter), yellow (limited entry) or green (occupancy permitted) tags as applicable. Tagging of the buildings is explained in Table 1, which reflects the relative damage to the structures by the earthquake. The area surveyed for structural damage is shown in Figure 1. The most severely damaged facilities were located in or around the San Fernando Valley and the City of Santa Monica. Only the buildings under OSHPD jurisdiction were surveyed.

The following summarizes the posting status at each of the 472 facilities:

- 11 facilities had at least one building red tagged.
- 16 facilities had at least one building yellow tagged.
- All red and yellow tagged buildings were located in a total of 23 facilities. For details of the posting of the buildings at these facilities, see Table 1. For non-structural damage at these buildings, see Table 2.
- 74 facilities were green tagged although there was some damage. For details of damage to these facilities, see Table 3.
- 375 facilities were undamaged and were green tagged.

[1]Office of Statewide Health Planning and Development, Sacramento, California

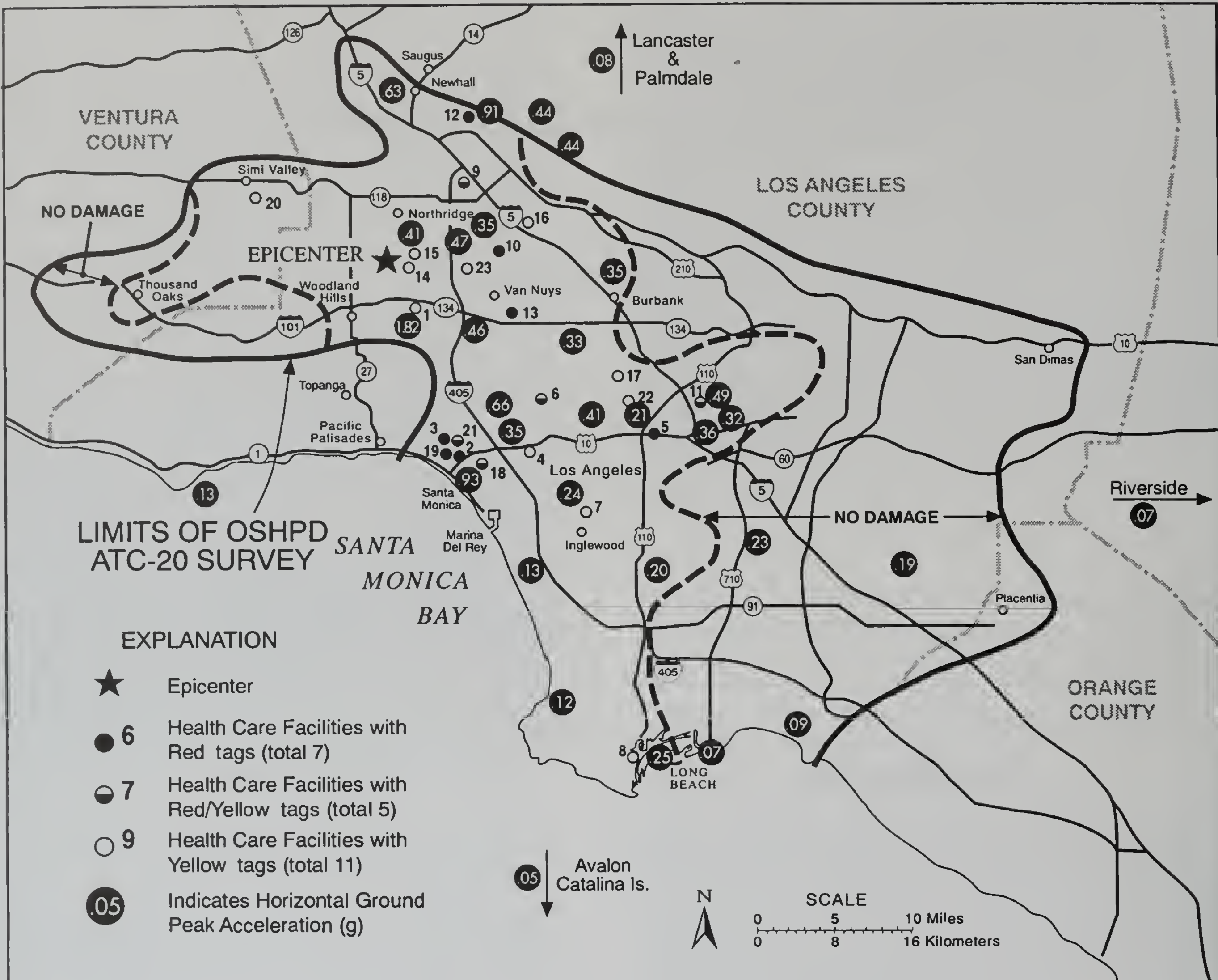


Figure 1. Location of health care facilities in the Northridge area that were surveyed for structural damage.

Table 1. Distribution and type of damage from the 1994 Northridge earthquake to hospitals and skilled nursing facilities (SNF) for 83 buildings at 23 facilities under the jurisdictiion of the Office of Statewide Health Planning and Development.

	Pre-Act Buildings			Post-Act Buildings		
	Red	Yellow	Green	Red	Yellow	Green
Hospital Buildings	9	14	22	0	1	30
SNF Buildings	3	4	0	0	0	0
Totals	12	18	22	0	1	30

Note: Red tag = unsafe, entry may cause injury or death.
Yellow tag = limited entry, off limits to unauthorized personnel.
Green tag = inspected, no restriction on use, lawful occupancy permitted.

DAMAGE TO PRE-ACT BUILDINGS

Red Tagged Buildings

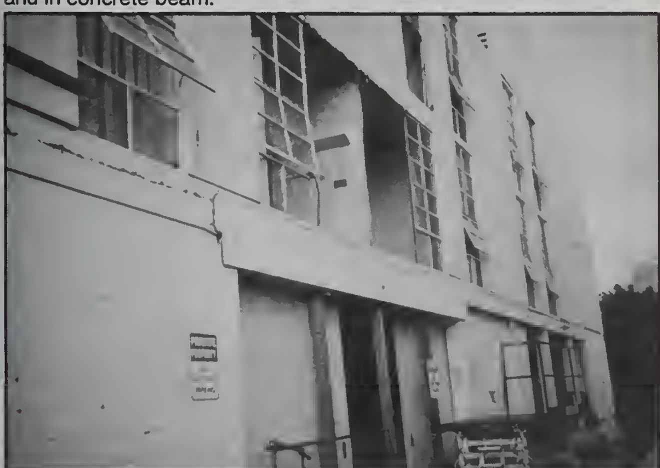
The following 12 pre-Act buildings were red tagged and evacuated, partially or completely, depending on the extent of damage.

(1) Bay Vista Health Care Center/Convalescent Hospital, Santa Monica

This is a 4-story poured in place reinforced concrete building with concrete shear walls. The columns and shear walls cracked at pour joints and along the diagonal direction of panels (Photo 1, a and b). Elevators, walls and partitions were damaged. The building remains unoccupied as of April 1, 1995.

Photo 1. (a) Bay Vista Health Care Center, a skilled nursing facility in Santa Monica, California. Failure occurred at the masonry wall-slab connection.

(b) Bay Vista Health Care Center, showing cracking in south wall and in concrete beam.



(2) Berkeley East Convalescent Hospital, Santa Monica

This is a four-story building constructed in 1972 to the City of Santa Monica building code. It sustained severe damage to the exterior reinforced brick masonry walls (Photo 2). The north wall at the first floor collapsed partially. The building remains unoccupied as of April 2, 1995.

Photo 2. Berkely East Convalescent Hospital, showing shear failure of wall adjacent to a window.

Photo 3. California Medical Center, showing inadequate concrete cover on columns at basement level. The corroded spiral ties failed under earthquake loading.

(3) California Medical Center, Los Angeles

This is a nine-story reinforced concrete building constructed in 1926. Six concrete columns were cracked (Photo 3). One column had cracks 1 inch to 2 inches wide. By February 8, 1994 the building was repaired and occupied.

(4) Schuman Building at Cedars Sinai Medical Center, Los Angeles

This eight-story concrete building with flat slab and shear walls had extensive hairline cracking of the shear walls. At least one exterior column had cracking at the second floor level (Photo 4). The building remains unoccupied as of April 1, 1995.

(5) Administration Building at Holy Cross Medical Center, Mission Hills

This three-story concrete building with steel beams in some locations was badly cracked at horizontal pour joints of concrete walls and at the support of steel beams (Photos 5a and 5b). This building was partially demolished voluntarily by the hospital authorities.

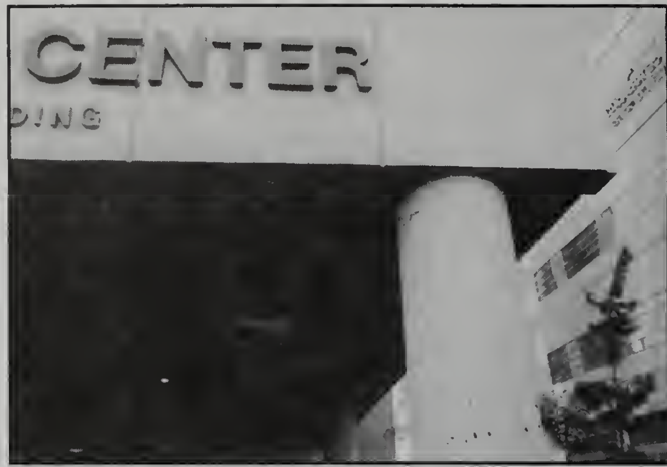


Photo 4. Cedars Sinai Medical Center, Schuman Building, showing cracking at the top of a column supporting the building. There was also shear wall cracking and broken windows in this building.

Photo 5a. Holy Cross Medical Center Administration Building showing failure at pour joints and connections.

Photo 5b. Close up of failed connection shown in photo 5a.Holy Cross Medical Center.

Photo 6. Kaiser Hospital, showing earthquake damage to penthouse structure on roof of hospital and damage to equipment inside the storage structure (north wall of building).

(6) Kaiser Hospital, penthouse for rooftop housing of mechanical equipment, Panorama City

This braced steel frame structure atop the existing pre-Act hospital building sustained severe damage to the structure and the equipment (Photo 6). The hospital building, though not tagged red, had severe water damage and broken glazing in the top four stories requiring temporary evacuation of the patients. Earthquake repairs have been completed.

(7) Psychiatric Hospital at Los Angeles County/USC Medical Center, Los Angeles

This nine-story concrete frame masonry shear wall building had severe structural and non-structural damage (Photo 7). Columns developed extensive "X" cracking at spandrels. Damage to elevators, mechanical and electrical equipment, water piping and interior walls and ceilings was reported. Building was evacuated and remains unoccupied as of November 1, 1994.

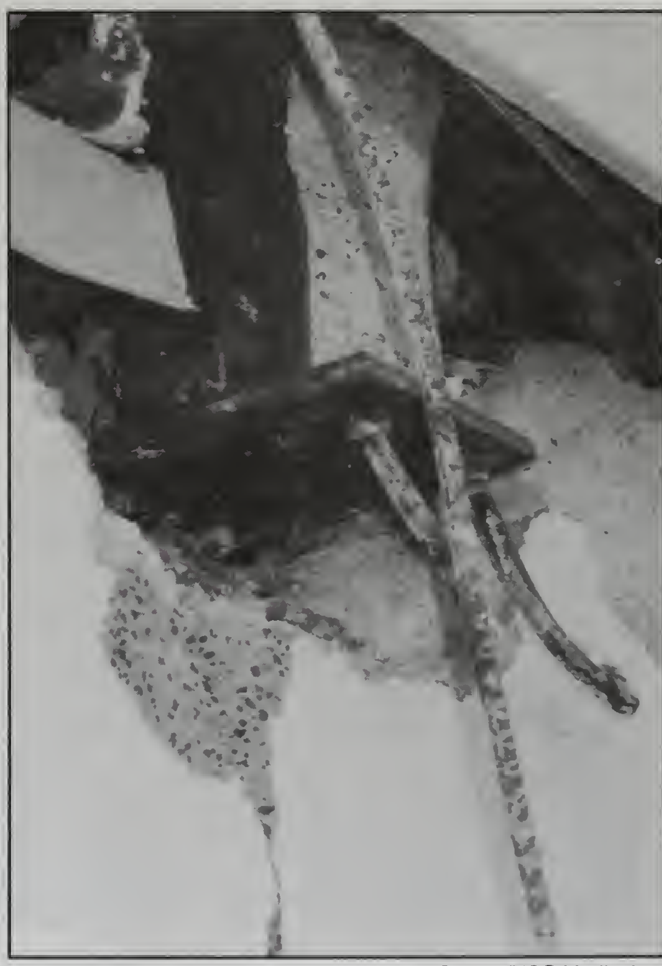


Photo 7. Psychiatric Hospital at Los Angeles County/USC Medical Center, showing cracking and separation of two perpendicular walls at the corner of the building on the second floor.

(8) Medical Center of North Hollywood

Penthouse structure and equipment sustained severe damage. Repairs were completed by January 22, 1994.

(9) Left Wing of the Santa Monica Convalescent Center, Santa Monica

This is a one-story SNF building with unreinforced masonry walls. Severe and extensive structural cracking of masonry walls was reported. Building was evacuated and remains vacant as of November 1, 1994.

(10) Tower Building at Santa Monica Hospital and Medical Center, Santa Monica

This is a nine-story plus basement, concrete shear wall building. Severe and extensive cracking of north and south shear walls and three concrete columns was reported. Elevators, mechanical and electrical equipment, fire sprinklers and interior walls were damaged. Extensive water damage was reported. The building was completely evacuated on January 17, 1994, but was partially reoccupied when posted yellow on January 21, 1994.

(11) North wing and (12) South Wing of St. John's Hospital and Health Center, Santa Monica

These are two separate eight-story concrete shear wall buildings. Severe cracking of shear walls was reported requiring complete evacuation. Extensive damage to elevators, electrical equipment, fire sprinklers, clay tile partitions and walls, glazing, ceiling and light fixtures was reported. In the North Wing the wall piers between closely spaced windows of the second story sustained "X" cracking and were shattered (Photo 8). The North Wing has been demolished. The South Wing building had severe damage to shear walls between the windows of the third story. It was temporarily repaired and opened on October 3, 1994.

The following general observations may be made about the structural damage to twelve red tagged pre-Act buildings:

- Eight buildings were of non-ductile reinforced concrete construction.
- Two were steel frame penthouses atop concrete buildings.
- One was a reinforced brick masonry building.
- One was a single story building of unreinforced masonry construction.
- Six of the twelve buildings were in Santa Monica and may have been subject to a ground motion similar to that recorded at Santa Monica City Hall with a peak ground acceleration of 0.93 g.

Yellow Tagged Buildings

The following 18 pre-Act buildings at sixteen facilities were yellow tagged during the week following the main earthquake on January 17, 1994.

(1) AMI Tarzana Regional Medical Center, Tarzana

Patient Tower (circa 1972), six-story plus penthouse building of concrete frame and post tensioned slab construction. Two concrete columns, stairs and landings were severely damaged. Mechanical and electrical equipment, fire sprinkler piping, ceilings, and partitions were damaged. Water damage.

(2) Brotman Medical Center, Culver City

Tower Building, seven-story plus basement with steel frame and concrete shear wall primary structure. Shear walls cracked, elevator counter weights

Photo 8. St. John's Hospital and Health Center, showing failure of shear wall on second story level of the North Wing and cracking and shattering around windows. The North Wing building was demolished.

Photo 9. Cedars Sinai Medical Center, Los Angeles, showing collapsed ceiling in lobby.

worked loose from rails as the frames supporting counter weights were damaged.

(3) Cedars Sinai Medical Center, Los Angeles

Thalian Building. Damage included localized collapse of ceiling and damage to equipment and water piping. Ceiling collapsed because it could not sustain the relative motion of the two primary structures at seismic separation joint (Photo 9).

(4) Daniel Freeman Memorial Hospital, Inglewood

One-story Boiler Plant of concrete construction. Minor damage to concrete columns and boiler foundations. Backing plate pulled loose on cabinets.

(5) Harbor View House (SNF), San Pedro

Five-story concrete frame, unreinforced masonry construction. Extensive structural and non-structural damage at 5th floor and roof. Partial evacuation. Repairs were scheduled to start in November, 1994.

(6) Los Angeles County/USC Medical Center, Los Angeles

Pediatrics Hospital. Eight-story concrete shear wall building. "X" cracking in columns at spandrels. Damage to elevators, mechanical and electrical equipment, water tank, and fire sprinklers. This building currently stands vacant.

(7) Medical Center of North Hollywood, Los Angeles

Hospital Tower. Four-story steel frame and concrete shear wall building. Damage to shear wall (Photo 10), to elevator counter weights, electrical equipment, and water pipes. Some interior water damage.

(8) Northridge Care Center (SNF), Reseda

Structural damage to entry canopy, non-structural damage on the interior.

Photo 10. Medical Center of North Hollywood, showing extensive cracking of shear wall at the southwest corner of the building where a window was added in a shear wall.

(9) Northridge Hospital Medical Center, Northridge

(a) "F" Tower (circa 1968). Five-story plus basement, steel frame, concrete shear wall building. Much cracking and spalling of concrete at various locations. Extensive loss of masonry veneer. Pounding damage at connectors to other buildings. Damage to elevators, mechanical equipment, water piping, fire sprinkler system, drywall interior partitions, ceilings, light fixtures. Severe water damage. Repair work continues as of November 1, 1994.

(10) (b) "G" Tower (circa 1974). Five-story plus basement. Extensive and severe structural and non-structural damage. Severe water damage, ceiling collapse. Repair work continues as of November 1, 1994.

(11) Pacifica Hospital of the Valley, Sun Valley

Three separate three-story plus basement concrete frame and reinforced masonry shear wall buildings. Severe damage to the masonry walls at stair wells and elevator shafts. Damage to elevators, mechanical and electrical equipment, and water piping. Stair stringer anchor bolts pulled out of wall support. Some water damage. Repairs have been completed.

(12) Queen of Angels/Hollywood Presbyterian Medical Center, Los Angeles

North Building (circa 1922 and 1926). Six-story concrete frame and shear wall building. Severe damage to shear walls. Damage to interior partitions and elevator shaft walls. Elevator damage.

(13) Santa Monica Convalescent Center (SNF), Santa Monica

Right Wing. One-story unreinforced masonry structure. Severe and extensive structural damage to walls. Building is unstable.

(14) St. John's Hospital and Health Center, Santa Monica

(a) Main Wing. Six-story concrete shear wall building. Severe and extensive cracking of shear walls, typical "X" cracking of concrete piers between windows, cracking along pour joints or random cracking. Damage to elevators, mechanical and electrical equipment, clay tile partition walls, glazing, ceilings, light fixtures. Damage to clay tile walls around stair wells along fire exit. Inoperable fire alarm system. Building was evacuated on January 20, 1994. After temporary repairs, the building was reoccupied on October 3, 1994.

(15) (b) Mental Health Center. Four-story steel frame building with concrete and brick masonry shear walls. Severe damage to shear walls. Building was evacuated on January 27, 1994. Building was temporarily repaired and it was reopened on April 18, 1994.

(16) Simi Valley Rehab and Nursing Center (SNF), Simi Valley (Ventura County)

One-story wood frame building with lath and plaster shear walls. Foundation cracked due to fissures in the ground under the building and extending into the parking lot. Potential hazard to vertical load support system. Extensive cracking of lath and plaster exterior walls. Damage to emergency generator, fire sprinklers, walls, partitions, glazing, ceilings and light fixtures. Building was evacuated and remains unoccupied.

(17) Temple Hospital, Los Angeles

Building (circa 1923). Six-story concrete frame building with unreinforced masonry for infill exterior walls and interior partitions. Severe damage to masonry infill walls. Cracks in concrete columns. Damage to elevator counter weights, fire sprinklers, plaster, light fixtures.

(18) Valley Presbyterian Hospital, Van Nuys

South Tower (circa 1961). Four-story concrete frame and shear wall building. Exterior walls of lath and stucco plaster cracked. Shear walls cracked. Damage to mechanical equipment, water piping, fire sprinklers. Minor damage to interior plaster walls and ceilings.

The following observations are made about the damage to the 18 yellow tagged pre-Act buildings:

- Most of the buildings had concrete or masonry shear walls for lateral load resistance in conjunction with steel or concrete frame vertical load resisting systems. Ductility of the shear walls may be questionable.
- One building had concrete frame only for vertical and lateral loads.
- One building was damaged by the failure of the ground under the building.

DAMAGE TO POST-ACT BUILDINGS

(1) Holy Cross Medical Center, Mission Hills

Main Building. This building is a replacement for the building which was severely damaged in the Sylmar earthquake of 1971. It is a four-story building with a penthouse for mechanical equipment at the roof level. The bottom two stories have shear walls and were not damaged. Above the second floor the primary structure consists of heavy steel moment frames along every column grid line in two directions. Moment connections are typical welded connections. Severe damage occurred in the penthouse to mechanical equipment and exterior walls.

Damage was also sustained by counter weights of one elevator, fire sprinkler system, laboratory pharmacy, and kitchen equipment. There was some water damage. The anchorages of the liquid oxygen tank on hospital grounds and a water tank in the central plant were also damaged. In the period immediately after the main earthquake on January 17, 1994, the above damage to the main building and to other pre and post Act buildings resulted in a temporary evacuation of the patients.

Investigation of possible damage to the welded joints of the steel moment frame commenced in April 1994. The building, structurally divided into parts A through D, was found to have damage to approximately 50 percent of the welded joints of the steel framing at the third floor and above. Types of damage at the bottom flange of the girder to column connection included a variety of brittle fracture patterns through girder, weld, heat affected zone behind the weld, part or whole thickness of column flange and across column flange and web. Fractures were also noted at web connections and at top flange to column connection. Backup bars to the full penetration groove welds were not removed at the time of the construction. Repairs of the welded joints commenced in June 1994 and are continuing (as of April 1, 1995) in phases.

(2) Los Angeles County Olive View Hospital, Sylmar

Six-story steel frame hospital building with concrete and steel shear walls. Patients were evacuated on January 17, 1994 due to damage to elevator counter weights, water piping, fire sprinkler piping, ceiling and extensive water damage. No primary structure damage was reported immediately after the earthquake. However, investigation is underway to determine damage to steel frame; some damage to steel member chord and collectors has been reported.

(3) Henry Mayo Newhall Memorial Hospital, Valencia

This is a 1 to 2-story steel moment frame building complex consisting of four seismically separate buildings. Damage survey immediately after the earthquake reported minor structural damage and damage to fire sprinklers and glazing. Damage survey currently underway to inspect the welded joints of moment frames indicates severe damage, mostly at the welded joint between bottom flange of girders and columns.

NON-STRUCTURAL DAMAGE

Data on different types of non-structural damage were compiled from the site surveys indicating damage regardless of the color of tag to any building. See photos 11 and 12 for non-structural damage to roof mounted equipment.

Photo 11. St. Johns Hospital, Santa Monica, showing damage to the roof-mounted cooling tower due to failure of beam support at the columns.

Photo 12. Cedar Sinai Medical Center, Los Angeles, showing a storage tank that shifted under restraining straps due to lack of positive tank anchorage in the longitudinal direction.

CONCLUSIONS

Pre-Act Hospital Buildings

Based on the data of damage to buildings at twenty-three facilities presented in Table 1, 60% of pre-Act hospital buildings in the sample were tagged red or yellow primarily due to structural damage.

Post-Act Hospital Buildings

None of the post-Act hospital buildings were tagged red and only one yellow tag was posted to the mechani-

Table 2. Non-structural damage is based on data from damage surveys at 82 buildings at 23 facitlities under OSHPD jurisdiction, where at least one building was tagged red or yellow.

Number of buildings where specified damage occurred				
Damaged Item or Type of Damage	Hospitals		Skilled Nursing and Intermediate Care Facilities	
	Pre-Act Buildings	Post-Act Buildings	Pre-Act Buildings	Post-Act Buildings
Elevators	10	4	2	0
Equipment Anchorage	14	4	3	0
Water Piping	8	5	2	0
Fire Sprinkler System	9	5	3	0
Water Damage	10	6	2	0
Interior Walls	12	8	5	0
Liquid Oxygen Tank	3	1	0	0
Glazing	2	2	2	0

Table 3. Non-structural damage is based on data from damage surveys at 74 green tagged facilities with some damage.

Number of buildings where specified damage occurred				
Damaged Item or Type of Damage	**Hospitals**		**Skilled Nursing and Intermediate Care Facilities**	
	Pre-Act Buildings	Post-Act Buildings	Pre-Act Buildings	Post-Act Buildings
Minor Structural	17	6	26	0
Elevators	9	2	0	0
Equipment Anchorage	11	2	13	0
Water Piping	4	2	0	0
Fire Sprinklers	7	5	6	0
Water Damage	7	5	4	0
Interior Walls	10	3	7	0
Liquid Oxygen Tank	0	0	1	0
Glazing	1	2	3	0

cal penthouse of Holy Cross Hospital. Post-Act hospital buildings provided life safety and substantial continuity of service, although the latter was compromised by extensive non-structural damage and water damage. Damage to the welded joints of steel moment frame buildings was unanticipated and not known in days immediately following the earthquake. The code requirements for the design and construction of welded moment frame buildings are changing so as to prevent the brittle and nonductile failure of the joints.

Bender, Sylvia, 1995, Earthquake damage to libraries *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 219-220.

EARTHQUAKE DAMAGE TO LIBRARIES

by

Sylvia Bender[1]

INTRODUCTION

The Northridge earthquake disrupted the services of 134 of the 317 public library facilities serving 12,400,000 people in the Los Angeles area (40% of the state population). Private and community colleges and universities were also hit. Across all types of academic institutions, libraries consistently sustained greater earthquake damage than other campus buildings, primarily because of the performance of book shelves.

Many of these libraries reopened within days of the quake after thousands of books, which had fallen to the floor, were reshelved. Closer to the epicenter, however, libraries were faced with more serious concerns ranging from collapsed bookstacks to structural damage. Preliminary cost estimates for recovery from public library damage range from $8,000,000 to $10,000,000.

PATTERNS OF DAMAGE

Location

Damage is correlated to distance from the epicenter; those closest sustained greater damage. With two exceptions, libraries on the eastern side of the San Fernando Valley remained open while those on the west were closed for weeks or months to complete repairs. The following locations received the greatest damage:

Los Angeles City Public Library branches in Chatsworth, Granada Hills, Woodland Hills, Reseda, Northridge, Canoga Park, Pacoima, Sylmar, Sherman Oaks, Van Nuys, North Hollywood, Eagle Rock and Los Feliz;

Los Angeles County Public Library branches in Valencia, Newhall and San Fernando;

Ventura County Library branches in Simi Valley and Fillmore, located just west of the San Fernando Valley;

Thousand Oaks Main Library, also just west of the San Fernando Valley;

Santa Monica Main Library;

CSU Northridge Oviatt Library;

UCLA Special Collections, Art Library, Engineering & Mathematical Sciences Library and the University Research Library.

Structural Damage

The most severely damaged library in the earthquake was the Oviatt Library on the California State University Northridge campus, the closest library to the epicenter. The visually striking exterior overhang and columns of the building along with facade panels either collapsed or leaned precariously. At least ten of the steel support beams were sheared off at ground level. The welds attaching the columns to their bases broke during the earthquake allowing the columns to shift. The entire building was closed to occupancy. The older wing of the building reopened for Fall semester 1994, but repair on the newer steel portion may take another two years.

Most of the Los Angeles Public Library branches in the San Fernando Valley were built in the 1950s and 1960s. Damage to these buildings ranged from minor to nearly complete destruction. The five worst cases included Chatsworth, Granada Hills, Northridge, West Valley Regional (Reseda) and Woodland Hills. Demolition will not be required as once feared. Initial investigations showed damage to load-bearing walls, water damage, ceiling beam damage, collapsed non-suspended ceilings and window damage.

[1]California Department of Conservation, Division of Mines and Geology, Sacramento, California

The Thousand Oaks Library reported nearly $2 million dollars worth of damage primarily caused by the collapse of a unique reflecting ceiling, which consisted of hundreds of 7-inch wide bright metal strips attached by 1/8-inch clips. The design successfully enhanced the facility's ambient lighting, but collapsed totally during the earthquake. The falling ceiling sheared off sprinkler heads and broke at least one water pipe. The library was the only commercial structure in the city of Thousand Oaks declared unsafe after the quake.

The Valencia Regional Library suffered considerable water damage to furnishings and books from broken water pipes. Although the building appears structurally sound, asbestos was exposed as was the case in several other older libraries.

At the UCLA University Research Library, an expansion joint between two building parts separated leaving a one-inch gap.

Shelving Damage

The most seismically vulnerable components in a library are the book stacks. Libraries as far away as UC Riverside lost books from their shelves. Collapse of shelving, however, was limited to the epicenter area and was dependent upon the type of reinforcement. In the CSU Northridge, Simi Valley and Valencia libraries, book stacks, which had recently been cross-braced and bolted to the floor and into walls, remained standing. Shelving which had not been upgraded was generally damaged beyond repair. Shelving on higher floors consistently dumped more books onto the floor. The new Central Library in Los Angeles found very few books on the floors of its four underground levels compared to the three upper levels.

Metal bookcases at the U.S. Courts Library in downtown Los Angeles, located on the 17th floor of the courthouse, "hopped" on top of books that had fallen to the floor. College of the Canyons in Santa Clarita reported a similar occurrence with shelving jumping "four or five inches" off the floor. The inherent weakness of the metal bookcases in the Courts Library resulted in twisted and bent shelving. Shelves also slid out of the cases during the quake.

Unbraced wooden shelving at the Fillmore branch of the Ventura County Library cracked, twisted and broke during the quake.

SIGNIFICANCE OF DAMAGE

On many of the college campuses in the affected region, the library proved to be the only damaged building. A 90-inch tall three-foot double-face, fully loaded book stack can easily weigh more than 1,400 pounds. Typically book stacks are grouped in rows of seven units each. A mere nine such rows set into motion during an earthquake represent more than 50 tons of weight transferring its energy to the building. Large libraries may have hundreds of such rows of book stacks.

In areas near the epicenter, complete destruction of shelving occurred in libraries not utilizing bracing whereas properly braced shelves sustained little, if any, damage. Even low shelving sustained damage without bracing. There is little consensus from the Northridge damage, however, on the most effective form of bracing. Is cross-bracing plus floor-bolting sufficient or should wall-bracing be added also? Other factors appear to be type of shelving, format of material shelved, height of the building, and orientation of the shelving relative to quake motion. Since neither quake nor building motion can be predicted with certainty, bracing from all sides may be necessary. Vertical cross-bracing which was hooked in place rather than welded popped out. Wooden and metal bookcase shelving underwent the greatest damage.

Toggle bolts held up better, for the most part, than either simple screws and washers or shields in securing shelves to walls. Shelving perpendicular to a wall and bolted, but not braced from the other end, tended to pull away from the wall. Bolting into lathe plaster or sheet rock proved insufficient.

EVALUATION OF OVERALL PERFORMANCE AND CONCLUSIONS

Seismic safety issues facing libraries are both serious and unique. Anchored and braced shelving performed well during the Northridge earthquake. Too much reliance is placed on anecdotal evidence, however, to provide a clear standard for the most appropriate bracing for specific shelving and building design conditions. A systematic engineering evaluation of performance of library shelving during earthquakes is needed.

REFERENCES

California State Library, Library Development Services Bureau, 1994, Northridge earthquake library damage file (includes correspondence, clippings, and Internet messages).

Flagg, Gordon, 1994, Libraries jolted by L.A. earthquake: American Libraries, v. 25, no. 3, p. 214-219.

Gibson, Liz, 1994, The Northridge earthquake, preliminary damage estimates for California libraries and institutions of higher education: California State Library Newsletter, no. 144, 12 p.

Pierce, Jeff, 1994, When the shaking stops. . . the seismic issue: Stacks, news from the Hopley Company, March-April, 2 p.

Matasović, N., Kavazanjian, E., Jr., Augello, A.J., Bray, J.D., and Seed, R.B., 1995, Solid waste landfill damage caused by 17 January 1994 Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 221-229.

SOLID WASTE LANDFILL DAMAGE CAUSED BY 17 JANUARY 1994 NORTHRIDGE EARTHQUAKE

by

Neven Matasović[1], Edward Kavazanjian, Jr.[1],
Anthony J. Augello[2], Jonathan D. Bray[2], and Raymond B. Seed[2]

ABSTRACT

Observations of damage to landfills indicate that the general performance of solid waste landfills during the Northridge earthquake was from good to excellent. None of the solid waste landfills surveyed showed any signs of major damage. However, a geosynthetic-lined landfill close to the zone of energy release experienced significant damage evidenced by tears in the geomembrane liner and two other geosynthetic-lined landfills at similar distances suffered moderate damage evidenced by cracking in interim cover soil at waste/natural ground transitions, breaking of gas extraction system header lines, and loss of power to the gas collection system. Several unlined and soil lined landfills also experienced moderate damage, as evidenced by cracking and limited downslope movement in cover soils. These observations, combined with the fact that no landfill with a geosynthetic cover has ever been subjected to strong ground motions, indicate that, despite the general observation of the good to excellent performance of solid waste landfills in past earthquakes, caution is warranted in the design of modern, geosynthetic-lined and/or covered landfills subject to seismic loading.

INTRODUCTION

The 17 January 1994 Northridge earthquake provides important observational data on the response of solid waste landfills to strong ground shaking. There are numerous active, inactive, and closed solid waste landfills within 62 miles (100 km) of the epicenter. In a study funded by the National Science Foundation, GeoSyntec Consultants (GeoSyntec) and the University of California at Berkeley (UCB) are compiling information on damage at 22 major landfills that experienced significant shaking (estimated free field peak horizontal ground accelerations in excess of 0.05 g). The location of each landfill is shown on Figure 1. These 22 landfills and their primary characteristics are summarized in Table 1. A brief description of the damage that occurred at these 22 landfills in the Northridge earthquake is provided herein. A more detailed description of the characteristics of each landfill and the damage that occurred due to the Northridge event will be provided in UCB/GeoSyntec (1995).

With the exception of the OII, BKK, Calabasas, Palos Verdes, and Simi Valley landfills, the solid waste landfills listed in Table 1 are classified by the State of California as Class III, municipal solid waste landfill facilities (MSWLF). OII, BKK, Calabasas, Palos Verdes, and Simi Valley landfills have (or have had) licensed hazardous waste disposal units (California Classes I and II), but also received municipal solid waste (MSW). MSW in the greater Los Angeles area has the following typical composition (by volume): demolition and construction waste (29%), residential waste (39%), commercial waste (21%),

[1]GeoSyntec Consultants, 16541 Gothard Street, Huntington Beach, California 92647
[2]Department of Civil Engineering, University of California, Berkeley, California 94720

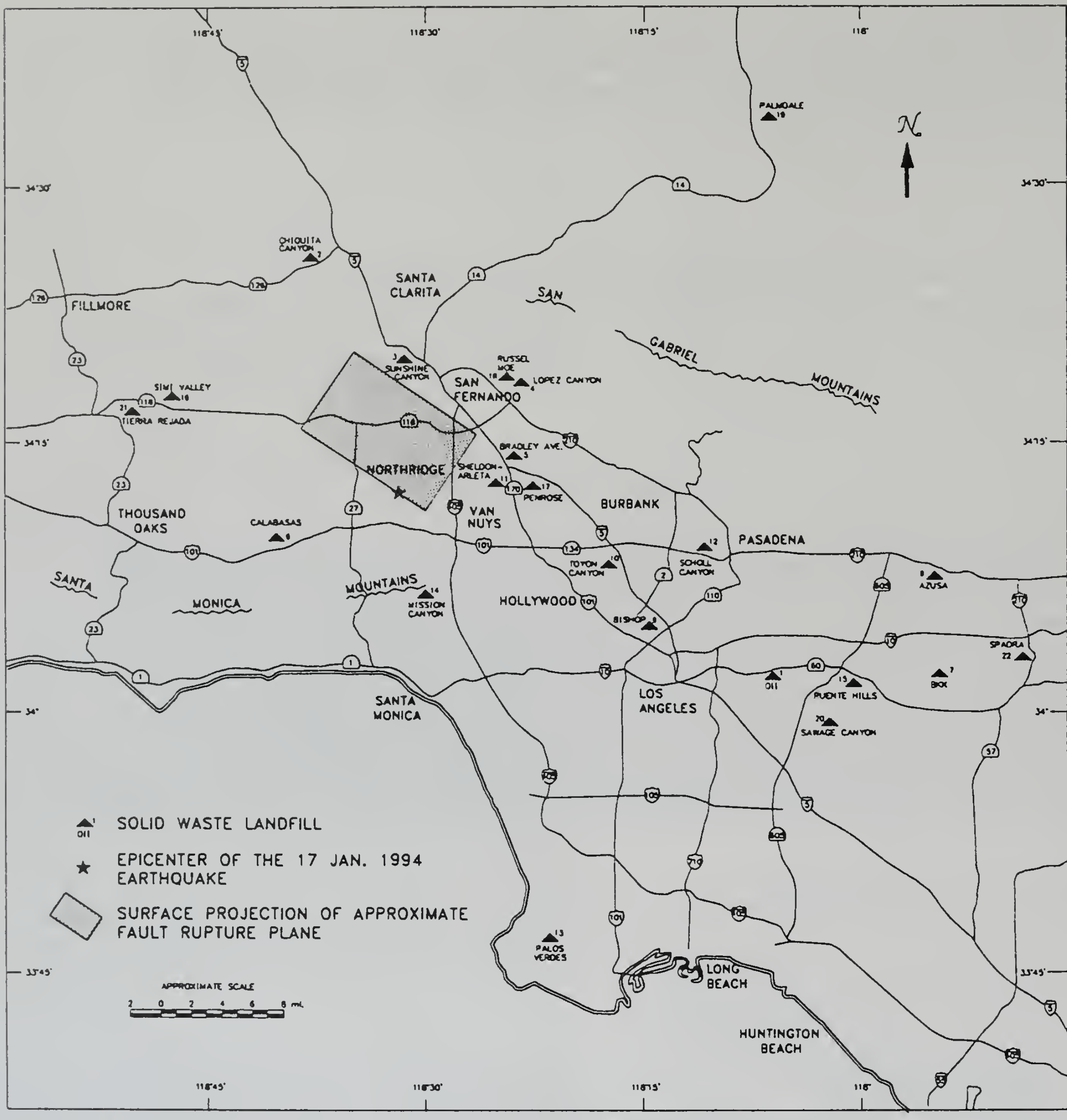


Figure 1. Major solid waste landfills within 100 km of the 17 January 1994 Northridge earthquake epicenter.

industrial waste (5%), miscellaneous waste (3%) and non-hazardous liquid waste (3%) (CoSWMP, 1984). Sewage sludge, occasionally disposed of at MSWLF, forms less than 1% of the waste accepted at MSWLF. Disposal of non-hazardous liquid waste in solid waste landfills was banned in California in 1985.

The primary elements of the four predominant solid waste landfill types in the greater Los Angeles area are shown on Figure 2. For the 22 landfills surveyed in this study, Table 1 presents their classification according to Figure 2, landfill size, the number of active, inactive, and closed landfill cells (waste units), and the type of containment system present at the landfill at the time of the earthquake. Containment system details depend to a large extent on the date of construction of the waste unit. In accordance with current state and federal regulations, after 9 October 1993, new waste units and lateral expansions of existing waste units that received waste had to have composite liners (a geosynthetic liner overlying a low permeability soil layer), and leachate collection and removal systems (LCRS) on their base and side slopes. Base and side slopes on which waste was discharged prior to 9 October 1993 may have only low permeability soil liners or may have no liner at all.

Table 1. An outline of solid waste landfills encompassed by this study.

SOLID WASTE LANDFILL	TYPE	LANDFILL AREA acres (ha)	ACTIVE CELLS	INACTIVE CELLS	CLOSED CELLS	ENGINEERED CONTAINMENT SYSTEM
1. OII	Gravel Pit Fill	190 (77)	None	2 (North and South Parcels)	None	None (Primary Landfill)
2. Chiquita Canyon	Canyon Fill	624 (253)	1 (Canyon C)	2 (Canyons A and D)	2 (Canyon B and the Primary Landfill)	Geosynthetic Liner System & LCRS (all other Canyons)
3. Sunshine Canyon	Side Hill Fill	230 (93)	None	1	None	Soil Liner
4. Lopez Canyon	Canyon Fill	166 (66)	2 (Areas C & AB+)	2 (Areas A & B)	None	Geosynthetic Liner System & LCRS (Canyon C)
5. Bradley Avenue	Gravel Pit Fill	209 (85)	1 (West Cell)	1 (East Cell)	None	Geosynthetic Liner System & LCRS (West Cell)
6. Calabasas	Canyon Fill	416 (168)	1 (Cell P Under Construction)	Several		Geosynthetic Liner System & LCRS (Cell P)
7. BKK	Canyon Fill	500 (200)	1	None	1 (Haz. Waste Unit)	Compacted Soil (Haz. Waste Unit)
8. Azusa	Gravel Pit Fill	302 (122)	1	None	None	Geosynthetic Liner System & LCRS (Partial Coverage)
9. Bishop Canyon	Canyon Fill	40 (16)	None	None	1	None
10. Toyon Canyon	Canyon Fill	90 (36)	None	1	None	LCRS & Subsurface Barrier
11. Sheldon-Arleta	Gravel Pit Fill	41 (17)	None	None	1	None
12. Scholl Canyon	Canyon Fill	430 (174)	1 (Southern Canyon)	None	1 (Northern Canyon)	None
13. Palos Verdes	Canyon Fill	300 (122)	None	None	3	None
14. Mission Canyon	Canyon Fill	400 (162)	None	None	3 (Canyons 1,2 & 3)	None
15. Puente Hills	Side Hill Fill; Canyon Fill	1,365 (552)	3	None	None	Geosynthetic Liner System & LCRS (Canyon 9)
16. Simi Valley	Canyon Fill	233 (94)	1(?)	1		Geosynthetic Liner System & LCRS; Compacted Soil
17. Penrose	Gravel Pit Fill	110 (45)	None	None	1	None
18. Russel Moe	Canyon Fill	15 (6)	None	None	1	None
19. Palmdale	Area Fill	65 (26)	1	None	None	None
20. Savage Canyon	Canyon Fill	45 (18)	1	None	None	
21. Terra Rejada	Canyon Fill	25 (10)	None	None	1	None
22. Spadra	Canyon Fill	323 (131)	1	None	None	Geosyntheic Liner System (Western half) & LCRS

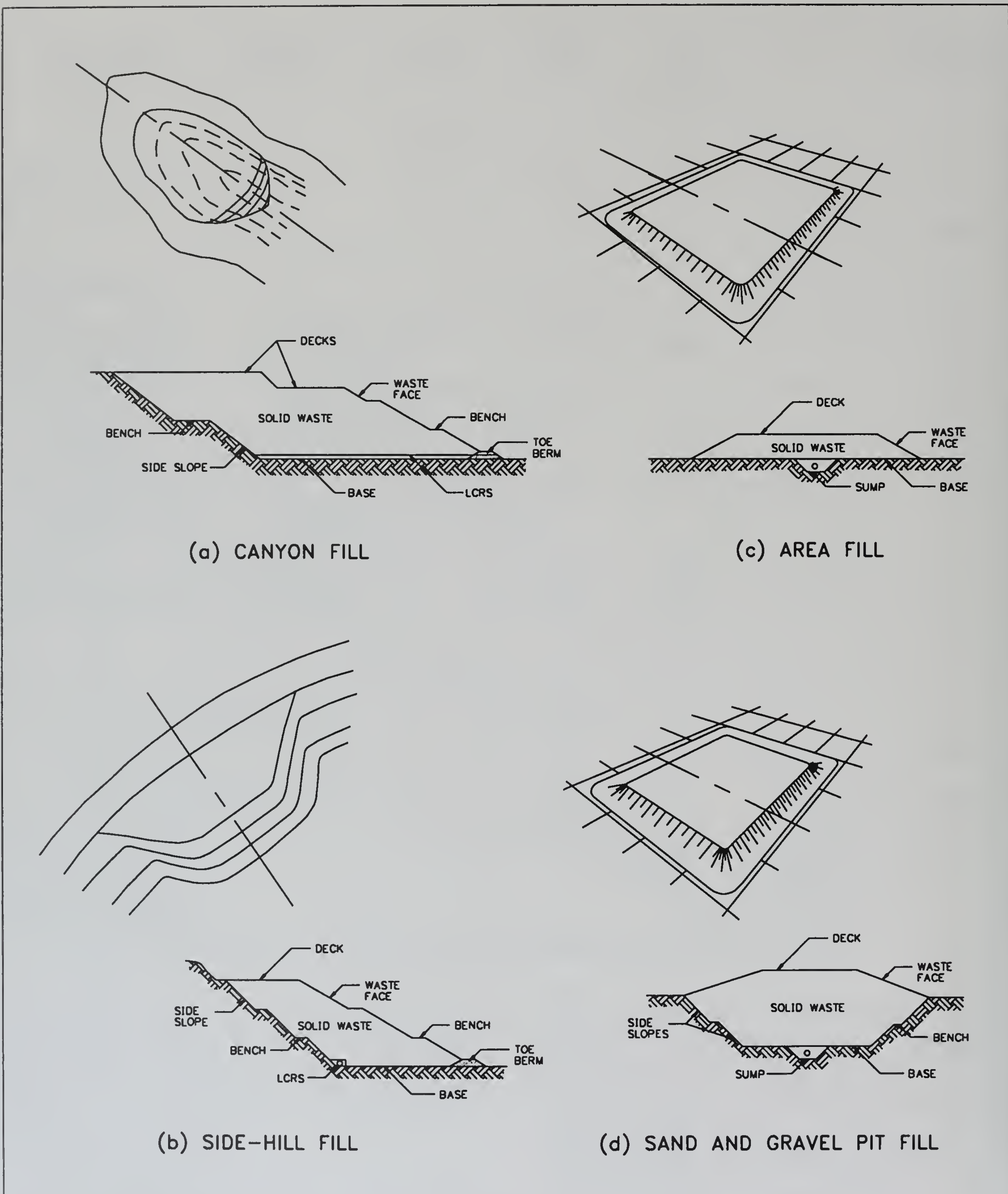


Figure 2. Predominant solid waste landfill types in the greater Los Angeles area.

All of the active and inactive waste cells surveyed after the earthquake were covered by daily or interim soil cover layers. California regulations require MSW to be covered daily with at least 6 in. (150 mm) of soil cover. On surfaces where waste has not been placed for more than 180 days, an interim cover (soil layer of at least 12 in. (300 mm) in thickness) is required. However, it is not uncommon for interim soil cover for an inactive waste unit to be over 3 ft (1 m) in thickness. All closed landfills identified in Table 1 had compacted soil covers. In accordance with California prescriptive standards, soil covers at closed landfills typically consisted of a protective vegetative soil layer a minimum of 12 in. (300 mm) thick underlain by a compacted low permeability soil barrier layer a minimum of 12 in. (300 mm) thick underlain by a compacted foundation layer a minimum of 24 in. (600 mm) thick. No geosynthetic covers were in place on major landfills subject to moderate or strong ground shaking in the Northridge earthquake. However, current regulations are likely to increase the number of landfills which have geosynthetic materials in their cover systems.

The inclination of active and interim waste slopes was typically 1.75H:1V - 2H:1V (horizontal to vertical). At the BKK and OII landfills, interim waste slopes were as steep as 1.3H:1V and 1.4H:1V respectively. At closed landfills, waste face slopes were typically 2H:1V or flatter. Side slopes that underlay waste in the canyon-fill and gravel pit type landfills were typically graded at 1.5H:1V (average grade). However, at the Chiquita Canyon and Bradley Avenue landfills, some side slopes underlying the waste fill approach 1H:1V. Gas collection systems were in place at approximately 50 percent of the surveyed landfills at the time of the earthquake and LCRS were in place at approximately 30 percent of the surveyed landfills. All of the landfills have some kind of surface water control system that typically includes water conveyance and storage structures. Various earth retention structures, such as toe berms, embankments and retaining walls, were used at the surveyed landfills for waste containment, surface water control, stability, and to facilitate access to the landfill. A detailed description of the primary elements of each of the surveyed landfills, including waste units, liner and cover systems, leachate collection and removal systems, gas collection systems, and ancillary structures will be provided in UCB/GeoSyntec (1995).

OBSERVED DAMAGE

Given the variety in landfill types, sizes, age and elements, it is difficult to precisely define damage categories for solid waste landfills. A simple methodology for solid waste landfill damage categorization, based upon impairment to the waste containment system and requirements for post-earthquake repair, was developed for this study. Categories of landfill damage are defined in Table 2. In establishing these damage categories, damage to structures beyond the waste mass footprint, including sedimentation basins, water and leachate conveyance and storage systems, flare stations, and other ancillary facilities, was not considered as critical as damage to the waste containment system. While continued serviceability of these structures may be essential to operation of the landfill's environmental protection system, these structures are conventional engineered facilities that do not require specialized damage categorization.

The approximate epicentral distance, the closest distance to the zone of energy release, free-field peak horizontal ground acceleration, and the level of damage

Table 2. Damage categories for solid waste landfills.

DAMAGE CATEGORY	DESCRIPTION
V. Major Damage	General instability with significant deformations. Integrity of the waste containment system violated.
IV. Significant Damage	Waste containment system impaired, but no release of contaminants. Damage cannot be repaired within 48 hours. Specialty contractor needed to repair the damage.
III. Moderate Damage	Damage repaired by landfill staff within 48 hours. No compromise of the waste containment system integrity.
II. Minor Damage	Damage repaired without interruption to regular landfill operations.
I. Little or No Damage	No damage or slight damage but no immediate repair needed.

in accordance with Table 2 are presented in Table 3 for the 22 landfills addressed by this study. The epicentral distance refers to the distance from the epicenter as determined by U.S. Geological Survey (34.213N and 118.537W) to the approximate geometric center of the landfill. The closest distance to the zone of energy release refers to the distance from the fault plane as interpreted by Stewart and others (1994) to the approximate geometric center of the landfill. With the exception of the OII landfill, the peak horizontal ground acceleration was determined by linear interpolation from the free field acceleration isopleth map (rock and soil sites) developed by Wentworth and others (1994). At OII, the free-field peak ground acceleration was obtained from strong motion instrumentation installed at the landfill (Hushmand Associates, 1994).

The damage categories assigned in Table 3 to each landfill are based on the post-earthquake inspections as reported by CIWMB (1994), Stewart and others (1994), GeoSyntec (1994a; 1994b), and Kavazanjian (1994). Available damage surveys included the OII, Chiquita Canyon, Sunshine Canyon, Lopez Canyon, Bradley, Calabasas, Azusa, Toyon Canyon, Scholl Canyon, Mission Canyon, Puente Hills, Simi Valley, Russell Moe, Palmdale, Savage Canyon, Tierra Rejada, and Spadra landfills. Data collection on earthquake-induced damage for the BKK, Bishop, Sheldon-Arleta, Palos Verdes, and Penrose landfills was still in progress at the time this study was prepared.

The most significant damage to landfills observed following the earthquake were two localized tears in the geomembrane component of the composite liner of up to 75 feet (23 m) at the Chiquita Canyon landfill. In both cases, the tears were above the level of the waste and were repairable, though specialty contractors were required to complete repairs. No disruption of the low permeability soil liner beneath the geomembrane was reported. Furthermore, no indication of disruption to the containment system below the top of the waste has been reported.

At the Lopez Canyon landfill, also within 10 miles (16 km) of the zone of energy release, CIWMB (1994) reported a small tear of uncertain origin approximately 6 to 8 in. (150 to 200 mm) in length in the filter geotextile for the side slope liner. No damage was observed to either the LCRS geonet or the underlying composite liner. A subsequent investigation attributed the tear in the geotextile to landfill operations and not to the earthquake (GeoSyntec, 1994b).

The most commonly observed damage to landfills in the Northridge earthquake was surficial cracking in cover soil near transitions between waste fill and natural ground areas. Such cracking may be attributed to the contrast in the seismic response characteristics between the relatively soft waste fill materials and the relatively stiff adjacent natural ground. Cracking of relatively brittle cover soil overlying relatively ductile waste fill was also observed at many landfills. At several sites, cracking in cover soils due to limited amounts of downslope movement (typically less than 6 in. (150 mm)) was observed. At most landfills where cracking of cover soil was observed, the cracks were typically 0.5 to 3 in. (12 to 75 mm) wide with 0.5 to 3 in. (12 to 75 mm) of vertical relief. At one site (Chiquita Canyon), the waste moved downwards a distance of over 12 in. (300 mm) along the entire geosynthetic-lined backslope of the active waste cell.

Some of the observed cracking and downslope movement at landfills may have been due to earthquake-induced settlement of the waste fill. However, previous studies of settlement at landfills has indicated that seismic shaking does not induce significant settlement of solid waste (Coduto and Huitric, 1990). While data on the seismically-induced settlement of solid waste in the Northridge earthquake may be forthcoming, it was not available at the time of the summary.

A temporary shutdown of the landfill gas extraction system occurred at a number of landfills due to the power loss during and after the earthquake. At several landfills, breaks in the landfill gas extraction system headers and condensate lines were reported. In all cases, operation of the gas extraction system was restored within 48 hours. Landfill gas extraction systems typically maintain small negative pressure in the waste mass during operation. Landfill operators report that it typically takes at least 48 hours after shutdown of the landfill gas system for positive pressures to develop. Therefore, a disruption of less than 48 hours to the landfill gas extraction system is not considered to be major or significant damage. At one closed landfill without an active gas extraction system (the Russell Moe landfill), reports of gas odors caused the trailer park on top of the landfill to be evacuated. Later reports attributed the gas odors to ruptured lines from propane tanks supplying the trailers. It should be noted that landfill gas fires are reported to have erupted at cracks in the cover of this landfill following the 9 February 1971 M 6.5 San Fernando earthquake; its zone of energy release lies directly beneath the site.

Table 3. Seismic response of solid waste landfills during the 17 January 1994 Northridge earthquake.

SOLID WASTE LANDFILL	EPICENTRAL DISTANCE miles (km)	DISTANCE FROM ZONE OF ENERGY RELEASE miles (km)	ESTIM. PEAK HORIZONTAL ACCELERATION g	DAMAGE CATEGORY (I-V)	DAMAGED ELEMENT
1. OII	27.9 (44.9)	26.7 (43)	0.25 - 0.26 g	Minor Damage (II)	Cover Soil
2. Chiquita Canyon	16.0 (25.8)	7.6 (12.2)	0.39 g	Significant Damage (IV)	Cover Soil; 2 Geomembrane Liner Tears
3. Sunshine Canyon	8.5 (13.7)	4.4 (7)	0.52 g	Moderate Damage (III)	Cover Soil
4. Lopez Canyon	10.5 (16.9)	5.2 (8.4)	0.44 g	Moderate Damage (III)	Cover Soil; Gas System
5. Bradley Avenue	9.5 (15.3)	6.7 (10.8)	0.45 g	Significant Damage (IV)	Cover Soil
6. Calabasas	9.5 (15.3)	14.4 (23.1)	0.25 g	Moderate Damage (III)	Gas System; Cover Soil
7. BKK	38.5 (62.0)	35.5 (57.2)	0.14 g	No Damage (I)	None
8. Azusa	37.5 (60.4)	32.1 (51.7)	0.10 g	No Damage (I)	None
9. Bishop Canyon	17.8 (28.7)	19.1 (30.7)	0.30 g	Little Damage (I)	Cover Soil
10. Toyon Canyon	14.5 (23.3)	13.8 (22.2)	0.25 g	Minor Damage (II)	Cover Soil; Gas Collection Header
11. Sheldon-Arleta	7.9 (12.7)	6.7 (10.7)	0.51 g	Minor Damage (II)	Cover Soil; Gas Collection Headers
12. Scholl Canyon	21.0 (33.8)	17.6 (28.4)	0.26 g	Moderate Damage (III)	Cover Soil
13. Palos Verdes	32.0 (51.5)	31.6 (50.8)	0.12 g	No Damage (I)	None
14. Mission Canyon	8.7 (14.0)	11.4 (18.4)	0.40 g	No Damage (I)	None
15. Puente Hills	33.5 (53.9)	30.9 (49.7)	0.11 g	No Damage (I)	None
16. Simi Valley	17.0 (27.4)	13.9 (22.3)	0.28 g	Minor Damage (II)	Cover Soil; Gas System; Leachate Pump
17. Penrose	9.0 (14.5)	7.6 (12.2)	0.35 g		
18. Russel Moe	10.0 (16.1)	4.9 (7.8)	0.44 g	Moderate Damage (III)	Cover Soil
19. Palmdale	35.0 (56.4)	25.5 (41.1)	0.07 g	Minor Damage (II)	Cover Soil
20. Savage Canyon	35.0 (56.4)	32.8 (52.8)	0.16 g	No Damage (I)	None
21. Terra Rejada	17.5 (28.2)	13.9 (22.4)	0.27 g	Minor Damage (II)	Cover Soil
22. Spadra	44.0 (70.8)	34.2 (55.1)	0.06 g	No Damage (I)	None

DISCUSSION AND CONCLUSIONS

The observations of damage to landfills described above and summarized in Table 3 indicate that the general performance of solid waste landfills during the 17 January 1994 Northridge earthquake was from good to excellent. None of the landfills surveyed showed any signs of major damage (Damage Category V). One geosynthetic-lined landfill within 10 miles (16 km) of the zone of energy release experienced significant damage (Damage Category IV), evidenced by tears in the geomembrane liner. Two other geosynthetic-lined landfills at a similar distance from the zone of energy release suffered only moderate damage (Damage Category III), evidenced by cracking in interim cover soil at waste/natural ground transitions, breaking of gas extraction system header lines, and loss of power to the gas collection system. Several unlined and soil lined landfills also experienced moderate damage (Damage Category III), as evidenced by cracking and limited downslope movement in cover soils.

These observations are in general agreement with the observations on landfill performance after the 1 October 1987 M 6.1 Whittier earthquake (TETC, 1988; Anderson and others 1992) and the 17 October 1989 M 7.1 Loma Prieta earthquake (Orr and Finch, 1990, Buranek and Prasad, 1991; Johnson and others 1991), wherein solid waste landfills subjected to strong ground motions were reported to all have performed satisfactorily (Damage Categories I to III). However, it should be noted that none of the landfills subjected to strong ground motions in either the Whittier or Loma Prieta earthquakes were lined with a geosynthetic liner. Furthermore, no landfill with a geosynthetic cover has ever been subjected to strong ground shaking from an earthquake.

Ground motions recorded by the strong motion instrumentation at the OII landfill have demonstrated that free field earthquake motions are not necessarily attenuated through solid waste landfill. In the Northridge earthquake, peak horizontal ground accelerations of 0.25 g and 0.26 g were recorded at the base and crest of the landfill respectively. Corresponding spectral acceleration amplification factors of between 4 and 8 were calculated for the 1 to 2 second period range (5 percent damping). In a series of other recent smaller earthquakes, peak horizontal acceleration amplification factors of 3 have been recorded and spectral acceleration amplification factors of greater than 10 (5 percent damping) have been calculated at OII landfill (Anderson and others 1992; Hushmand Associates, 1994). Response analyses using solid waste properties back calculated from the observations of strong ground motions at OII indicate that the amplification potential of solid waste may be similar to that of soft soil (Kavazanjian and Matasović, 1995).

These observations, combined with observation of damage to the geomembrane liner at one landfill in the Northridge event and the fact that no landfill with a geosynthetic cover has ever been subjected to strong ground motions, indicate that, despite the general observation of the good to excellent performance of solid waste landfills in past earthquakes, caution is warranted in the design of modern, geosynthetic-lined and/or covered landfills subject to seismic loading.

ACKNOWLEDGMENTS

Financial support was partially provided by the National Science Foundation under Grants Nos. CMS-9416261 and CMS-9422161. This support is gratefully acknowledged. The authors thank Mr. Charles Dowdell and Mr. John Hower of the Los Angeles County Sanitation Districts who visited several of the sites mentioned in this paper and generously provided their field reconnaissance data. Special thanks are extended to Mr. Sam Lessani of GeoSyntec Consultants who helped with data collection.

REFERENCES

Anderson, D.G., Hushmand, B. and Martin, G.R., 1992, Seismic response of landfill slopes: Proceedings of the Stability and Performance of Slopes and Embankments - II, Berkeley, California, v. 2, p. 973-989.

Buranek, D. and Prasad, S., 1991, Sanitary landfill performance during the Loma Prieta earthquake: Proceedings of the Second International Conference on Recent Advances in Geotechnical earthquake Engineering and Soil Dynamics, St. Louis, Missouri, p. 1655-1660.

CIWMB, 1994, Observations of landfill performance, Northridge earthquake of January 17, 1994: California Integrated Waste Management Board, Closure and Remediation Branch, 4 p. (plus attachments).

Coduto, D.P. and Huitric, R., 1990, Monitoring landfill movements using precise instruments, *in* Landva, A. and Knowels, G.D., eds., Geotechnics of Waste Fill - Theory and Practice, ASTM STP 1070: American Society for Testing and Materials, Philadelphia, PA, p. 358-370.

CoSWMP, 1984, Solid Waste Management Plan - Terrenial Review: Report, Los Angeles County, Vol. I, Figure 1 (Revision A, 1985).

GeoSyntec, 1994a, Observations of landfill performance during the 17 January 1994 Northridge earthquake: Internal Report, GeoSyntec Consultants, Huntington Beach, California.

GeoSyntec,1994b, Assessment of performance of the Disposal Area C liner system during the Northridge earthquake of 17 January 1994 and of damage to Geotextile and Geonet observed on 18 January 1994, Lopez Canyon sanitary landfill, Lake View Terrace, Los Angeles: Memorandum to Solid Waste Management Division, Bureau of Sanitation, City of Los Angeles by GeoSyntec Consultants, Huntington Beach, California, 6 p.

Hushmand Associates, 1994, Landfill response to seismic events: Report prepared for the USEPA Region IX, Hushmand Associates, Laguna Niguel, California.

Johnson, M.E., Lundy, J., Lew, M. and Ray, M. E., 1991, Investigation of sanitary landfill slope performance during strong ground motion from the Loma Prieta earthquake of October 17, 1989: Proceedings of the Second International Conference on Recent Advances in Geotechnical earthquake Engineering and Soil Dynamics, St. Louis, Missouri, p. 1701-1706.

Kavazanjian, E.,Jr., 1994, Performance of the geosynthetic liner system in the Northridge earthquake, an interview: Geotechnical Fabrics Report, March 1994, p. 18-24.

Kavazanjian, E., Jr. and Matasović, N., 1995, Seismic analysis of solid waste landfills: Proceedings of the Geoenvironment 2000, ASCE Specialty Conference, New Orleans, Louisiana, p. 1066-1081.

Orr, W.R. and Finch, M.O., 1990, Solid waste landfill performance during the Loma Prieta earthquake, *in* Landva, A. and Knowels, G.D., eds, Geotechnics of Waste Fill - Theory and Practice, ASTM STP 1070: American Society for Testing and Materials, Philadelphia, Pennsylvania, p. 358-370.

Stewart, J.P., Bray, J.D., Seed, R.B. and Sitar, N., 1994, Preliminary report on the principal geotechnical aspects of the January 17, 1994 Northridge earthquake, Report No. UCB/EERC-94/08: College of Engineering, University of California at Berkeley, Berkeley, California, 238 p.

TETC, 1988, In place stability of landfill slopes, Spadra Landfill, Los Angeles, California, Report No. 88-640-2: The Earth Technology Corporation, Long Beach, California.

UCB/GeoSyntec, 1995, Seismic performance of solid waste landfills, Joint Research Report, Civil and Environmental Engineering Department: University of California, Berkeley and GeoSyntec Consultants, Huntington Beach, California (in preparation).

Wentworth, C.M., Borcherdt, R.D., Mark, R.K., and Boore, D.M. , 1994, Maps of peak horizontal and vertical accelerations recorded for the Northridge, California, earthquake of January 17, 1994 and general geology of the epicentral region: U.S. Geological Survey Open-File Report 94-197, Menlo Park, California, 3 p.

SECTION IV

Earthquake Response and Recovery Plans

Real, C.R., and Petersen, M.D., 1995, Provisional seismic zoning of portions of Los Angeles and Ventura counties following the January 17, 1994 Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 231-239.

PROVISIONAL SEISMIC ZONING OF PORTIONS OF LOS ANGELES AND VENTURA COUNTIES FOLLOWING THE JANUARY 17, 1994 NORTHRIDGE EARTHQUAKE

By

Charles R. Real[1] and Mark D. Petersen[1]

INTRODUCTION

The January 17, 1994 Northridge earthquake may become the most costly natural disaster in U.S. history. Heavily urbanized portions of Los Angeles, Ventura, and Orange counties that were seriously affected by this event will probably be in a state of recovery for many years. As new code provisions are likely to develop from the growing inventory of structural damage, so is a better understanding of how the local geology influenced damage and loss from this devastating earthquake. Reconstruction is well underway, and seismic zoning is in progress to insure new construction will not be as vulnerable in a future event.

Following the devastating 1989 Loma Prieta earthquake, the California Legislature established the Seismic Hazard Mapping Act in 1990, which mandates the State Geologist to designate seismic hazard zones for use by local government in regulating the seismic safety of new construction. Because the program is new and reduced funding has prevented full implementation, zone maps for affected areas were not available following the Northridge earthquake. In response, the Federal Emergency Management Agency, Governor's Office of Emergency Services, and the California Seismic Safety Commission expressed the need for rapid delineation of seismic hazard zones in the affected area, to facilitate earthquake resistant reconstruction.

This report summarizes a federally-funded six- month effort to prepare provisional seismic hazard zone maps for the area affected by the Northridge earthquake. This area includes sixteen 7 1/2 minute quadrangles (Figure 1) for which ground failure hazards have been assessed, and a larger region for which a probabilistic seismic ground motion analysis has been performed. Criteria for zone delineation, analysis procedures, data sources, sample zone maps and suggested uses are discussed. Before addressing these topics, it is beneficial to review the general provisions of the Seismic Hazard Mapping Act in order to provide a clear distinction between "provisional" and "official" seismic zoning.

SEISMIC HAZARD MAPPING ACT

The Seismic Hazard Mapping Act requires that zones be designated that identify areas prone to ground shaking and related ground failures caused by earthquakes. The concept of the Act is patterned after the Alquist-Priolo Special Studies Zone Act (Hart, 1994), and followed recommendations of a two-year needs assessment for seismic hazard information (Holden and Real, 1990). The Act was signed into law on September 21, 1990 and became effective April 1, 1991. The Act is codified in the Public Resources Code as Division 2, Chapter 7.8, and amends, repeals, and adds new sections of law. The purpose of this act is to encourage land-use management policies and regulations that will reduce and mitigate earthquake hazards, and assist cities and counties in preparing their general plans.

The principle through which the Act operates requires the State to notify local government of seismically hazardous areas. Notification by the State results in a transfer of responsibility to the jurisdiction in which the land lies, and in turn to the property owner (Real and Holden, 1991). To accomplish this, the Act calls for the delineation of seismic hazard zones that identify areas of high potential for ground failures such as amplified ground shaking, liquefaction, and earthquake-induced landslides. The purpose of seismic hazards zones is to show local officials where a geotechnical site investiga-

[1]California Department of Conservation, Division of Mines and Geology, Sacramento, California

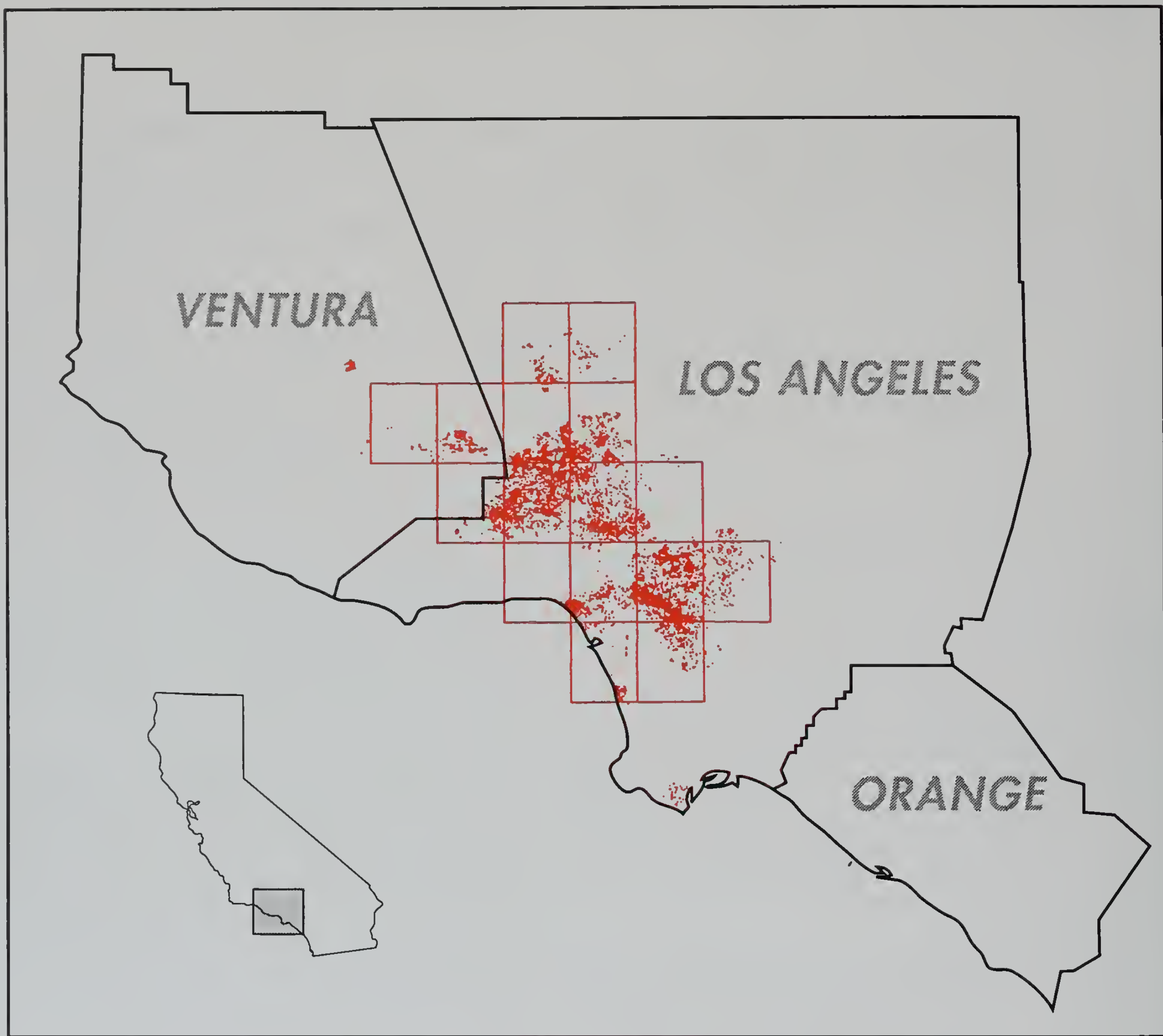


Figure 1.Tri-county study area for which probabilistic ground motion analysis has been performed, and the location of 7 ½ minute quadrangles covering the area damaged by the January 17, 1994 Northridge earthquake for which ground failure hazards have been assessed. Dense dot pattern is the location of red- and yellow-tagged buildings ranging from moderate to heavy damage.

tion should be required prior to the issuance of a construction permit. These investigations must be conducted by Registered Civil Engineers or Certified Engineering Geologists and should determine the severity of potential seismic hazards affecting the building site and recommend appropriate mitigation.

Under the provisions of the Act, the State Mining and Geology Board appointed an advisory committee composed of earth scientists, engineers, local government planners and insurance officials to help develop policies and regulations. A two-day workshop was convened in which 50 experts in earthquake hazards exchanged ideas on methods of evaluating seismic hazards and formulating appropriate mapping criteria. Working groups were formed to provide advice on the development of mapping and site investigation and review guidelines during the codification process. Formal regulations for implementation were approved by the State Office of Administrative Law in January, 1992, and codified as Title 14, Chapter 8, Article 10 of the California code of Regulations.

SEISMIC HAZARD ZONING PROJECT

The State Geologist is charged with designation of seismic hazard zones. To facilitate this process the California Department of Conservation, Division of Mines and Geology (DMG) established the Seismic Hazard Evaluation and Zoning Project. Goals are to zone the principal urban areas by the year 2000 and major growth areas by the year 2010, keeping pace with urbanization thereafter.

Official Seismic Hazard Zones are the product of a three-dimensional integration of geotechnical and geological data based on surface mapping and thousands of subsurface borings. Analysis is conducted according to the "Guidelines for Delineating Seismic Hazard Zones" (DMG) that were prepared during the policy development phase described previously. An advanced, geotechnically-oriented geographic information system (GIS) was developed and is used extensively in the evaluation process (Real, 1993). Based on experience from a pilot study undertaken with the City of San Francisco, a zoning project for a given jurisdiction is expected to take about 1 to 3 years depending on its size.

PROVISIONAL SEISMIC ZONING

Purpose

The purpose of provisional seismic zoning following the Northridge earthquake is to rapidly identify potentially seismically unstable areas to (1) facilitate cost-effective distribution of mitigation funds pursuant to the Stafford Act, and (2) provide interim seismic hazard zones to assist immediate reconstruction efforts while the more lengthy process of official zoning is underway.

The area for which provisional seismic zonation has been completed is shown in Figure 1, and includes most of Los Angeles County and a portion of the eastern edge of Ventura County. The areal extent is based on the distribution of reported structural damage caused by the Northridge earthquake. This area will be most affected by reconstruction and would immediately benefit from seismic zoning.

Provisional seismic zoning included two principal tasks: (1) estimation of future ground motions, and (2) mapping locations susceptible to future ground failures. These tasks were performed over a period of 9 months, and are summarized below. See Petersen and others (1995), and Real and others (1995) for a detailed technical discussion of the methodologies employed.

Future Ground Motions

We assessed the seismic ground motion hazard (peak acceleration and 5 percent damped spectral acceleration) at a 10 percent probability of exceedance in 50 years for the three counties impacted by the 1994 Northridge earthquake. Since these maps will be used for zoning and for making risk mitigation decisions by state and local government agencies, the maps incorporate source parameters and models that are consistent with the broad range of current scientific opinion. The Southern California Earthquake Center (SCEC) has facilitated consensus-building among scientific and engineering experts for many of the parameters that are used in assessing the seismic hazard in southern California (Jackson and others, 1995). Therefore, we adopted the SCEC model as the foundation of our model. Details of the DMG seismic source model and the integration of the seismic, geologic, and geodetic data sets can be found in a paper by Petersen and others (1995) and are described briefly below.

The SCEC seismic source model was modified with additional slip rate and geologic information to develop a source model with scale and detail appropriate for the tri-county area (Petersen and others, 1995). Many of the important faults used in the hazard analysis are shown in Figure 2. The maximum magnitude on each of these faults was calculated using the empirical relation between fault length and magnitude derived by Wells and Coppersmith (1994). Our hazard assessment not only incorporates seismicity on these mapped faults, but also allowed 25 percent of the hazard to occur as background earthquakes located throughout the tri-county area. These background sources account for earthquakes on unmapped or hidden structures (such as the fault that ruptured during the Northridge earthquake) and faults less than about 15 km and are oriented with strike and dip defined by the average structural trend within the zone.

The DMG source model incorporates seismic, geodetic, and geologic information. Generally, the geologic slip-rate data is used to assess the earthquake recurrence along fault sources, the historic seismic data to assess the rate of background seismicity, and the geodetic data as a validity check for the model. We also incorporate various combinations of the Gutenberg-Richter truncated exponential and characteristic distributions to describe the magnitude-frequency distributions along faults and for background seismicity (Petersen and others, 1995). The ground motion hazard is calculated using a modified version of the program FRISK (McGuire, 1976) and three equally weighted attenuation relationships of Boore and others (1993), Cambell and Bozorgnia (1994), and K. Sadigh (1994, written communication), accounting for style of faulting and various site conditions.

The peak horizontal ground acceleration (pga) map for alluvial site conditions is shown in Figure 3. This map may be useful in characterizing regional variations in seismic hazards in southern California, but should not be used as data for detailed site-specific estimates of ground shaking in the earthquake-resistant design of individual structures. The maps indicate a high hazard over the entire tri-county area, exceeding 0.4 g (pga) nearly everywhere. The hazard in the Los Angeles basin is quite uniform and generally falls between 0.4 to 0.5 g. The ground motion near the Palos Verdes Fault and the northern flank of the Los Angeles basin exceeds 0.5 g for this 10 percent in 50 year hazard. Ground motions

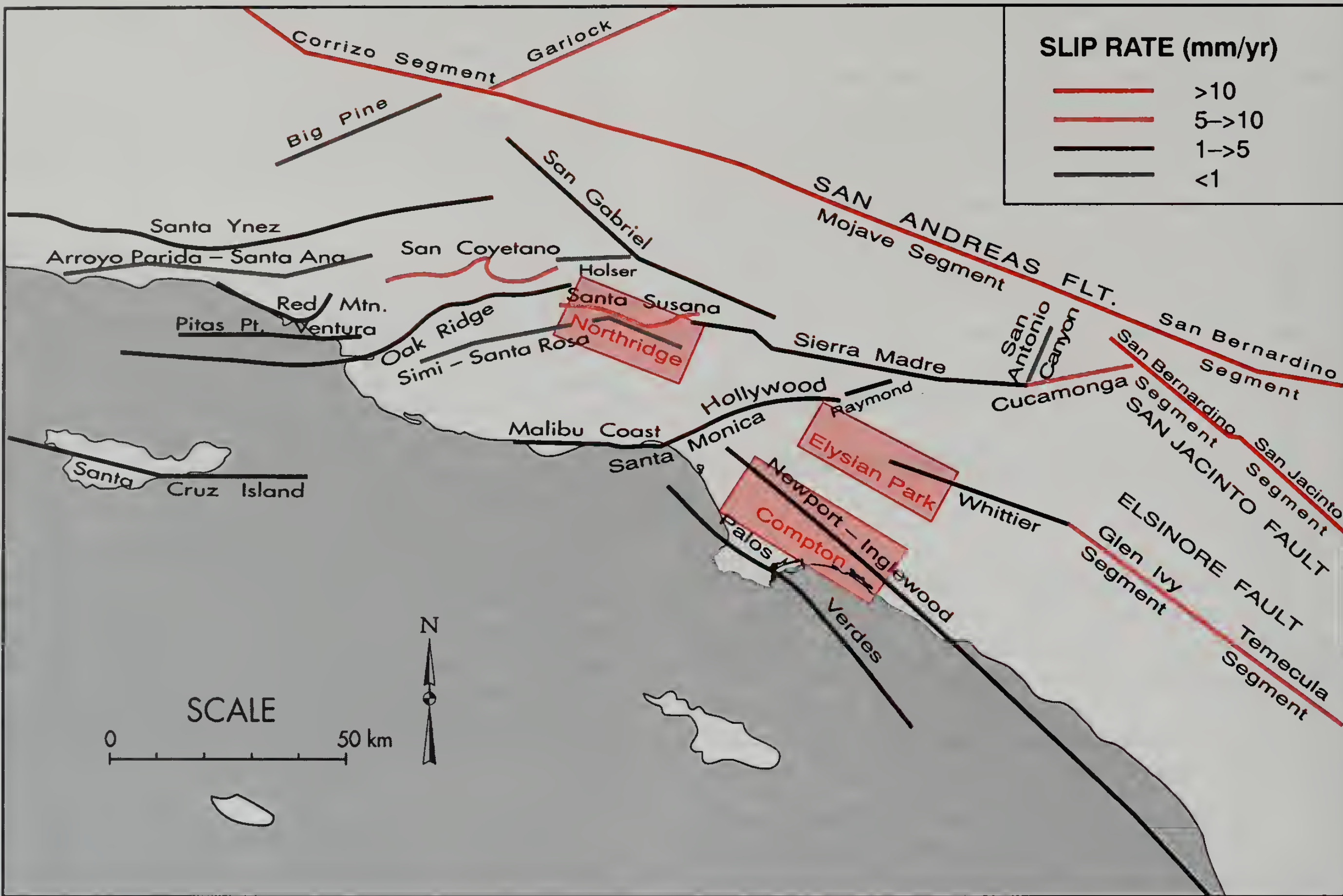


Figure 2.Tri-county region of southern California showing the locations of important faults used in the hazard assessment. Faults are color coded according to the estimated slip rates obtained from geologic studies.

exceeding 0.6 g are locally confined to the vicinity surrounding the Transverse Ranges (for example, the San Fernando and Ventura areas) and near the San Andreas, San Jacinto and Elsinore faults.

We also analyzed the quality and uncertainties associated with the source parameters of the seismic hazard analysis and computed the uncertainties in the hazard estimates using Monte Carlo stochastic techniques (Petersen and others, 1995). The variability studies indicate that for sites located in Los Angeles and Northridge, the difference between the mean and 95 percent confidence limits for pga range is between ± 0.1 and 0.3g at the 10 percent in 50 year exposure.

FUTURE GROUND FAILURES

Because official seismic zoning is time consuming it was necessary to employ a simple, expedient method to fulfill the immediate need. We used a simplified hazard evaluation model based on existing surface geological and topographical information and damage and geologic effects experienced during the 1994 Northridge and the 1971 San Fernando earthquakes. Provisional zone maps will be replaced by official zone maps as they are completed.

The hazard evaluation process employed for the delineation of provisional hazard zones is similar for landslides and liquefaction, and has been discussed in detail (Real and others, 1995). Geologic units are classified according to strength criteria independently for each hazard, and mapped over the study area (Tables 1 and 2). The areal extent of these units are spatially intersected with areas of shallow ground water for liquefaction hazard, and with slope categories for landslide hazard to identify the areal extent of hazard susceptibility. Because of the discrete nature of geologic units, spatial analysis was done using a vector-based GIS. In contrast, the continuous nature of topographic data was more efficiently analyzed for slope stability using a raster-based GIS.

Conservative criteria have been chosen to define each hazard such that susceptibility is equivalent to hazard potential given the level of expected future ground motions shown in Figure 3. Accordingly, it is believed

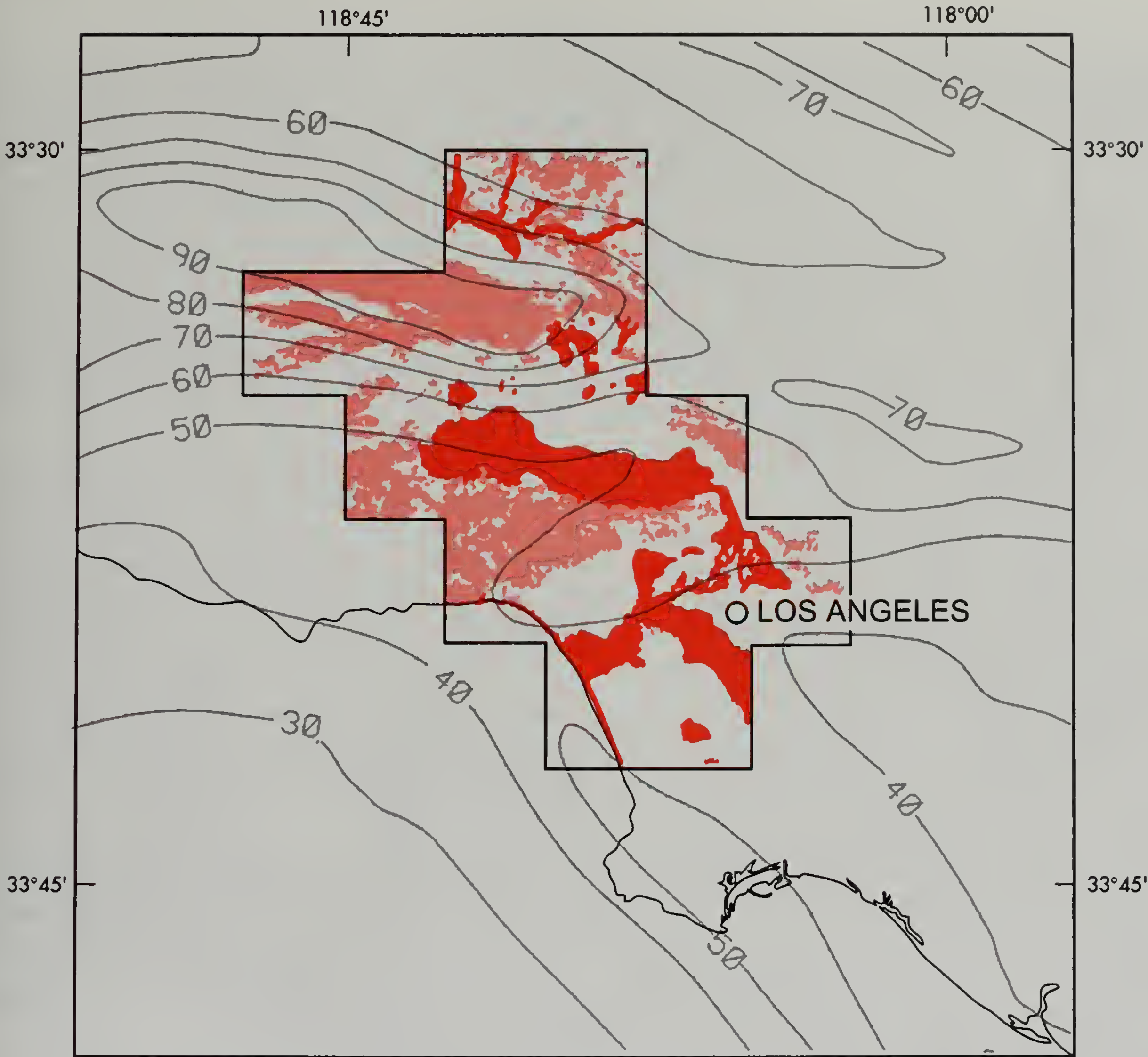


Figure 3. Southern California region showing peak ground acceleration (random component) exceeded at 10 percent probability in 50 years for alluvial site conditions. Also shown are provisional seismic hazard zones which delineate areas of potential ground failure (liquefaction shown in pink and landslides shown in red).

Table 1. Liquefaction zone criteria (shaded area is in zone) (Real and others, 1995).

GEOLOGIC UNIT	DEPTH TO GROUNDWATER	
	>40 ft.	< 40 ft.
Qa, Qg	low	high
all other	low	low

Table 2. Landslide hazard zone criteria (shaded area is in zone) (Real and others, 1995).

STRENGTH CATEGORY	SLOPE CATEGORY			
	0 - 25% (0 - 4:1)	25 - 50% (4:1 - 2:1)	50 - 67% (2:1 - 1.5:1)	>67% (>1.5:1)
A (strong)	low	low	low	high
B (moderate	low	low	high	high
C (weak)	low	high	high	high

that most earthquake-induced ground failures have occurred within the designated provisional zones and will probably continue to do so in the future.

Liquefaction

The criteria and procedures used to identify provisional liquefaction hazard zones is more simplified than for official zones. Provisional zones are defined by areas of artificial fill, Holocene or late Holocene soil deposits saturated at depths less than 40 feet (Table 1). Evidence of ground failures commonly associated with liquefaction at depth (sand blows, lateral spreading, differential settlement and fissuring) and associated structural damage caused by the Northridge earthquake also helped to delineate zone boundaries in a few areas.

Surface lithology was obtained from geologic maps of the Dibblee Foundation (1990-92), Castle (1960), Irvine (1989; 1990), Poland (1959), Treiman (1986a,b), Weber (1982), and Saul (unpublished), and soil maps of the U.S. Soil Conservation Service. Soil maps dating from the 1940s back to the early 1900s were used because they were prepared on a planimetric base and could be compared with contemporary geologic mapping. Only soil surveys that contain laboratory measurements of grain size were used, which permitted an age-texture based classification of geology on the more recent geologic maps. The work of Tinsley and others (1985) also helped to classify geology for susceptibility to liquefaction for much of the study area.

Depth to shallowest ground water (including perched levels) was obtained from regional ground water investigations by Mendenhall (1905), Leighton and Associates (1990), Tinsley and others (1985), California Water Rights Board (1962), and reports of the California Department of Water Resources (1961, 1966). This information was supplemented by borings from the California Department of Transportation and vintage topographic maps that show features indicative of high ground water, such as swamps and marshlands. Where possible, the historic ground water high is used. Although decades of water pumping for agricultural use dramatically lowered the water table in many areas, conversion to urban land use over the past three decades has been accompanied by a continuing rise in ground water levels in many areas. The assumption used in this analysis is that areas of historic high water table are probably good indicators of where high water may occur in the future.

This information was used to identify where artificial fill, Holocene alluvium (Qa) or Holocene river wash (Qg) is saturated at depths less than 40 feet. By definition, these areas delineate provisional liquefaction hazard zones.

Landslides

The criteria used to delineate provisional landslide hazard zones is simple and is based on a classification of the study area into terrain units characterized by strength and slope gradient (Table 2). Geologic units identified on the source maps were grouped according to material strength based on lithology, past performance, and to a lesser extent, structural features such as the orientation of bedding planes and joints and fracture density (Real and others, 1995). Information on past performance was obtained from private consultants and from the City of Los Angeles, and from DMG staff who have worked in the area for many years.

Slope gradient was determined from 1:24,000 digital elevation models (DEM) of the U.S. Geological Survey (U.S. GeoData, 1990). To reduce random errors, the DEMs were first smoothed to remove isolated peaks and pits. Slope gradient was calculated using the smoothed grid, and the resulting slope grids were then processed to determine the spatial distribution of slope categories shown in Table 2. Finally, the slope category grid was spatially intersected with the geologic strength grid to identify landslide susceptibility. The resulting susceptibility grid was densified to 5 meters, and then converted to a vector format for zone delineation and presentation.

Previous landslide inventories obtained from airphoto interpretation were used as a reality check on the validity of hazard zones. Final zone maps were prepared by removing all zones having an area of less than 6 acres. Given the limited resolution of the DEMs used, it is believed that appropriate slope classification is not reliable for areas less than about 6 acres.

RESULTS

Provisional seismic hazard zones are shown as filled areas superimposed on the ground motion contours of Figure 3. Approximately one third of the mapped quadrangle area is covered by seismic hazard zones, with the area covered by liquefaction and landslide zones being roughly equal. Because of the complex nature of hillslope topography, provisional landslide zones are highly fragmented and occur most continuously where steep slopes and weak earth materials coexist. In contrast, the generalized grouping of young, soft unconsolidated earth materials and assumptions of continuity of shallow ground water has resulted in more continuous provisional liquefaction hazard zones. Coincidence of future high ground shaking and weak ground conditions highlight areas where priority should be given for hazard mitigation in a regional sense.

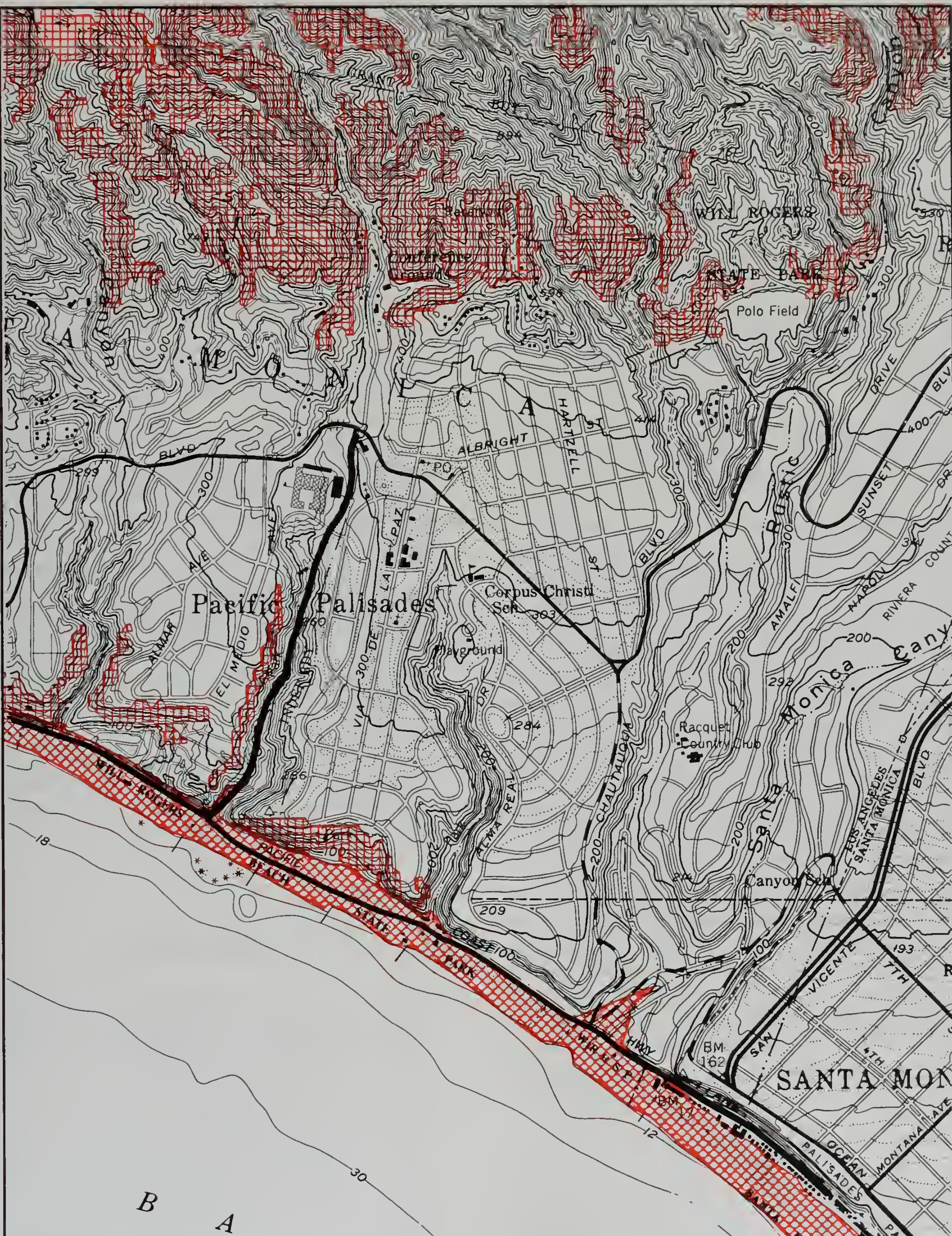


Figure 4. Portion of the provisional seismic zone map for the 7 1/2 minute Topanga quadrangle near Pacific Palisades. Vertical and horizontal cross-hatch indicates landslide hazard zone, and diagonal cross-hatch indicates liquefaction hazard zone.

Figure 4 shows an enlarged portion of the Topanga 7 1/2 minute quadrangle with provisional zones for liquefaction and landslides indicated as patterned areas. Careful inspection of the landslide hazard zones reveal the inability of the chosen digital data and analysis methods to identify all steep slopes of limited areal extent. For example, the cliff failure that dramatically separated a portion of a home near Chautauqua Road in Pacific Palisades was not recognized by the methods employed. The slope gradient is underestimated along steep cliffs and pointed noses of narrow ridges in mountainous areas. Because of the inconsistency or incompleteness with which steep sloping terrain of limited areal extent can be identified, there are areas of steep slope and increased hazard not recognized by provisional seismic hazard zones.

The analyses presented here are necessarily limited in order to provide timely products. Zoning can be improved by carrying the analysis into the subsurface, incorporating geotechnical boring data, and by a more thorough calibration of geologic conditions with the occurrence of slope failures triggered by the Northridge earthquake. Sediments can be tested and quantified as to their susceptibility to liquefaction permitting potentially liquefiable layers to be identified that have no surface manifestation. Preparation and analysis of higher resolution DEMs can permit inclusion of terrain parameters that are correlated to other factors affecting the stability of hillsides such as geologic structure and topographic geometry that can strongly influence hydrologic conditions. Higher resolution DEMs, improved gradient algorithms, and manual editing employed as part of a more thorough analysis should significantly reduce the limitations of provisional seismic hazard zones.

The scale and methods used to designate provisional zones limits their use for site-specific purposes. They are generalized representations of the actual hazard at the site, and only indicate an increased likelihood of hazard. Practical difficulties in mapping large areas at large scales and the paucity of data preclude identification of all hazardous areas. As a result, there will always be some hazard unzoned and some areas within a zone that have no hazard.

CONCLUSION

Provisional seismic hazard zone maps have been prepared for the area most affected by the Northridge earthquake, using a simplified, expedient procedure. While primarily intended to be used to assist distribution of federal disaster mitigation funds, they could temporarily serve to trigger site investigations for new construction until official seismic hazard zones become available. It is expected that provisional seismic hazard zones will be short-lived as plans are already underway to supersede them with official versions in the coming months. Provisional zones should facilitate recovery from the Northridge earthquake disaster during the interim.

ACKNOWLEDGMENTS

Many DMG staff worked on this project. Mark DeLisle, Richard Greenwood, Ralph Loyd, Jack McMillan, and Cindy Pridmore prepared provisional liquefaction hazard zones. Tim McCrink, Pam Irvine, Mike Silva, and Jerry Treiman prepared provisional landslide hazard zones. William Bryant, Chris Cramer, and Tousson Toppozada performed the ground motion hazard analysis. Robert Moskovitz provided GIS support. Ross Martin and Joy Sullivan assisted in graphic design.

Many individuals from local agencies provided useful information. Key individuals are: John Butcher, Joseph Cobarrubias, Rand Disko, and Neil Spiva of the City of Los Angeles; George Berg, Michael Kuhn, and Robin Rector of the City of Simi Valley; Dave Kehrlein of the Office of Emergency Services; Laurent McReynolds and Frank Stockel of Los Angeles Department of Water and Power, and Richard Gailing of the Southern California Gas Company. The valuable information they have provided will continue to be used to seismically zone the tri-county area affected by the January 17, 1994 Northridge earthquake.

This study was supported by disaster relief funds made available by the Federal Emergency Management Agency and the California Governor's Office of Emergency Services.

REFERENCES

Boore, D.M., Joyner, W.B., and Fumal, T.E., 1993, Estimation of response spectra and peak accelerations from western North American earthquakes — An Interim Report: U.S. Geological Survey Open-File Report 93-509, 72 p.

California Department of Transportation, Office of Engineering Geology: File for Log of Test Borings, various dates.

California Department of Water Resources, 1961, Planned utilization of the ground water basins of the coastal plain of Los Angeles County—Appendix A, Ground water geology: California Department of Water Resources Bulletin 104, 181 p.

California Department of Water Resources, 1966, Planned utilizations of ground water basins, San Gabriel Valley—Appendix A, Geohydrology: California Department of Water Resources Bulletin 104-2, 229 p.

California Water Rights Board, 1962, Report of referee, City of San Fernando: California Superior Court, County of Los Angeles, no. 650079: v. 1, 258 p.

Campbell, K.W. and Bozorgnia, Y., 1994, Near-source attenuation of peak horizontal acceleration from Worldwide Accelerograms Recorded from 1957 to 1993: Proceedings of the Fifth U.S. National Conference on Earthquake Engineering, July 10-14, 1994, Chicago, Illinois: Earthquake Engineering Research Institute, v. 3, p. 283-292.

Castle, R.O., 1960, Geologic map of the Baldwin Hills area, California: U.S. Geological Survey Open-File Map, scale 1:12,000.

DMG (unpublished document), Guidelines for mapping seismic hazard zones: California Department of Conservation, Division of Mines and Geology, 10 p.

Dibblee, T.W., 1989, Geology of the Los Angeles quadrangle: Dibblee Geological Foundation Map DF-22, scale 1:24,000.

Dibblee, T.W., 1991, Geology of the Beverly Hills and Van Nuys (south 1/2) quadrangles: Dibblee Geological Foundation Map DF-31, scale 1:24,000.

Dibblee, T.W., 1991, Geology of the Hollywood and Burbank (south 1/2) quadrangles: Dibblee Geological Foundation Map DF-30, scale 1:24,000.

Dibblee, T.W., 1991, Geology of the San Fernando and Van Nuys (north 1/2) quadrangles: Dibblee Geological Foundation Map DF-33, scale 1:24,000.

Dibblee, T.W., 1991, Geology of the Sunland and Burbank (north 1/2) quadrangles: Dibblee Geological Foundation Map DF-32, scale 1:24,000.

Dibblee, T.W., 1992, Geology of the Calabasas quadrangle: Dibblee Geological Foundation Map DF-37, scale 1:24,000.

Dibblee, T.W., 1992, Geology of the Oat Mountain and Canoga Park (north 1/2) quadrangles: Dibblee Geological Foundation Map DF-36, scale 1:24,000.

Dibblee, T.W., 1992, Geology of the Topanga and Canoga Park (south 1/2) quadrangles: Dibblee Geological Foundation Map DF-35, scale 1:24,000.

Hart, E.W., 1994, Fault-rupture hazard zones in California: California Department of Conservation, Division of Mines and Geology Special Publication 42, revised 1994, 34 p.

Holden, R.E. and Real, C.R., 1990, Seismic hazard information needs of the insurance industry, local government, and property owners in California - an analysis: California Department of Conservation, Division of Mines and Geology, 83 p.

Irvine, P.J., 1989, Landslide hazards in the north half of the Calabasas Quadrangle, Los Angeles and Ventura counties, California, Landslide Hazard Identification Map No. 20: California Department of Conservation, Division of Mines and Geology Open-File 89-18.

Irvine, P.J., 1990, Landslide hazards in the Simi Valley area, Los Angeles and Ventura counties, California, Landslide Hazard Identification Map No. 22: California Department of Conservation, Division of Mines and Geology Open-File 90-17.

Jackson, D.D., Aki, K., Cornell, C.A., Dieterick, J.H., Henyey, T.L., Mahdyian, M., Schwartz, D., and Wood, S.N., 1995, Seismic hazards in southern California — probable earthquakes, 1994-2024: Bulletin Seismological Society of America, v. 85.

Leighton and Associates, 1990, Technical appendix to the safety element of the Los Angeles County General Plan: Hazard Reduction in Los Angeles County, v. 1-2.

McGuire, R.K., 1978, FRISK — Computer program For sesimic risk analysis using faults as earthquake sources: U.S. Geological Survey Open-File Report 78-1007, 71 p.

Mendenhall, W.C., 1905, Development of underground waters in the western coastal plain region of southern California: U.S. Geological Survey Water-Supply Paper 139, 103 p.

Petersen, M.D., Cramer, C.H., Bryant, W.A., Reichle, M.S., and Toppozada, T.R., 1995, Preliminary seismic hazard assessment for Los Angeles, Ventura, and Orange counties, California affected by the January 17, 1994 Northridge earthquake; Submitted to: Bulletin Seismological Society of America.

Poland, J.F., Garrett, A.A., and Sinnott, A., 1959, Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California: U.S. Geological Survey Water-Supply Paper 1461, 423 p.

Real, C.R., 1993, A geotechnically-oriented GIS for seismic hazard mapping *in* Frost, J.D. and Chameau, J.A., eds., Geographic Information Systems and Their Application in Geotechnical Earthquake Engineering: ASCE , p. 90-94.

Real, C,R., DeLisle, M.J., and McCrink, T., 1995, Provisional seismic zoning for ground failures in portions of Los Angeles and Ventura counties following the January 17, 1994 Northridge earthquake; Submitted to: Bulletin Seismological Society of America.

Real, C.R. and Holden, R.E., 1991, Special Study Zones, a viable approach to zonation for ground shaking hazards: Proceedings of the 4th International Conference on Seismic Zonation, Stanford University, 3, p. 181-187.

Tinsley, J.C., Youd, T.L., Perkins, D.M., and Chen, A.T.F., 1985, Evaluating liquefaction potential, *in* Ziony, J.C., ed., Evaluating Earthquake Hazards in the Los Angeles Region: U.S. Geological Survey Professional Paper 1360, p. 263-315.

Saul, R.B., unpublished, Geology of the Mint Canyon Quadrangle, Los Angeles County, California: California Department of Conservation, Division of Mines and Geology.

Treiman, J.A., 1986, Landslide hazards in the west half of the Newhall [7.5'] Quadrangle, Los Angeles County, California: Landslide Hazard Identification Map No. 2: California Department of Conservation, Division of Mines and Geology Open-File 86-06.

Treiman, J.A., 1986, Landslide hazards in the east half of the Newhall [7.5'] Quadrangle, Los Angeles County, California: Landslide Hazard Identification Map No. 7: California Department of Conservation, Division of Mines and Geology Open-File 86-16.

U.S. GeoData, 1990, Digital elevation models: National Mapping Program, Technical Instructions, Data Users Guide 5, U.S. Geological Survey.

Ward, S.N., 1994, A multidisciplinary approach to seismic hazard in southern California: Bulletin Seismological Society of America, v. 84, p. 1293-1309.

Weber, F.H., Hsu, E.Y., Saul, R.B., Tan, S.S., and Treiman, J.A., 1982, Slope stability and geology of the Baldwin Hills, Los Angeles County, California: California Department of Conservation, Division of Mines and Geology Special Report 152.

Wells, D.L. and Coppersmith K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin Seismological Society of America, v. 84, p. 974-1002.

Andrews, R., 1995, Emergency response and recovery after the Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 241-245.

EMERGENCY RESPONSE AND RECOVERY AFTER THE NORTHRIDGE EARTHQUAKE

by

Richard Andrews[1]

INTRODUCTION

Within minutes of the Northridge earthquake, officials with the Governor's Office of Emergency Services (OES) had launched the statewide response. Warning controllers in OES headquarters in Sacramento alerted OES staff immediately, and within the hour the State Operations Center (SOC) had been activated.

The SOC was responsible for coordinating state agency response to assist local governments during the first 24-hour period, for collecting, verifying and disseminating intelligence, preparing situation reports for the Governor, coordinating all public information activities, and activating the state's mutual aid response system. As requests for help poured into the SOC from local governments and the regional operations centers, agency representatives quickly responded by deploying available resources and seeking additional help as needed.

The SOC was also responsible for bringing together and coordinating conference calls among state and federal response agencies to identify issues and solve problems related to water distribution, medical system delivery and support, and the initial aspects of temporary shelters. At the peak of operations, more than 100 OES and other state agency representatives were assigned to the SOC.

Due to the extensive damage to interstate and state roads, the California Highway Patrol worked closely with Caltrans to manage traffic throughout the affected area.

Over 2,600 members of the California National Guard distributed food and water, set up tents to protect thousands of quake victims from the rain, and provided security to areas where curfews had been established. With the use of its aircraft, the California National Guard also conducted damage assessment from the air and provided medical and health assistance by transporting victims and medical personnel.

COOPERATIVE EFFORTS

The California Department of Forestry and Fire Protection (CDF) provided over 600 personnel to support OES in applying the state's newly established Standardized Emergency Management System (SEMS) based on the Incident Command and Multi-Agency Coordination Systems, concepts initially developed by the fire services. CDF personnel are well versed and trained in the system and assisted OES in staffing the planning and intelligence, logistics, operations, administration and finance functions. CDF played a critical role in supporting operations of the Post Disaster Safety Assessment Program in La Canada.

The OES Regional Emergency Operations Center (REOC) in Los Alamitos was activated within one hour of the quake. OES personnel also reported to the various Emergency Operations Centers activated by local governments in the quake-struck area. The REOC remained operational on a 24-hour basis for several weeks, providing support to local jurisdictions, filling resource requests and collecting intelligence and damage reports.

Representatives from utilities, social services, Civil Air Patrol, the Individual Mobilization Augmentees program, Military Department and selected local govern-

[1]Director, Governor's Office of Emergency Services, Sacramento, California

ments reported to the REOC. Other agencies providing mutual aid support included the California Conservation Corps (CCC), California Department of Corrections, Emergency Medical Services Authority, California Department of Forestry and Fire Protection, Department of Transportation (Caltrans) and Department of Health Services.

The American Red Cross, Salvation Army, Federal Emergency Management Agency (FEMA), Metropolitan Water District, and the Orange County and San Diego County Health Departments also dispatched representatives to work in the SOC, REOC, local EOCs and elsewhere as needed.

A scientific clearinghouse was established within 10 hours of the earthquake to provide a central coordination point for collecting and disseminating reports on seismology, geology and structural damage. A number of other state agencies and private research organizations cooperated with OES on operating the clearinghouse, thereby providing critical disaster intelligence reports.

CALIFORNIA MUTUAL AID SYSTEM

The California Mutual Aid System is founded on a concept of self-help and neighbor-assisting-neighbor. Following the Northridge earthquake, some local agencies did not have enough resources to deal with the large number of law enforcement, fire, medical and public information activities. Requests for help went to the REOCs and to the SOC where the requests were relayed to the appropriate agencies for response. The first mutual aid request came soon after the earthquake had struck when local agencies asked for an aerial reconnaissance damage survey, which OES delegated to the California National Guard.

SEARCH AND RESCUE

Among the emergency response units called upon within the first few hours following the quake were the state's newly formed urban search and rescue task forces, created after the 1989 Loma Prieta earthquake by OES to detect and extract people from collapsed structures. Of the eight 56-member teams in California, six were deployed to help after the Northridge earthquake. The task forces from the City of Los Angeles and the County of Los Angeles extracted eight people from the collapsed Northridge Meadows apartment complex. They also freed a man trapped in the parking garage at the Northridge Fashion Center shopping mall.

Teams from Arizona and Puget Sound, Washington, modeled after the ones in California, were also dispatched to Los Angeles.

RESPONSE PLAN EFFECTIVENESS

Local Level

The overall response to the Northridge earthquake was extremely effective, particularly at the local level. City and county law and fire officials quickly identified the most serious situations and immediately dispatched the necessary resources to those locations. All the fires started by the earthquake were extinguished within five hours of the quake, and all sites requiring search and rescue operations had been identified and searching begun within the first few hours.

Local jurisdictions were quick to tackle the problem of people driven from their damaged homes and without a place to go. For example, the City of Filmore had opened temporary shelters by 6:00 a.m., just an hour and a half after the quake struck.

The response by local jurisdictions was so effective that most additional resources provided by the mutual aid system were not needed. Additionally, the response by local and state resources was completed before federal responders arrived in the state.

Communication Problems

Despite the overall effectiveness of the response, certain problem areas emerged. Communications proved to be a recurring problem throughout the response.

For instance, the local communications systems quickly became saturated. It is difficult to maintain central control of dispatching fire and response equipment when the telephone lines and radio channels are overloaded. So individual fire engine companies operated independently until communications were restored. This particular aspect of disaster response—communications saturation—is recognized by local disaster plans, so officials were prepared to respond accordingly.

Hospital communications were also impacted by the quake. Without adequate communications among various hospitals and other medical care facilities and responders, officials could not easily determine which hospitals could accommodate more patients, how much damage the facilities had incurred, and which hospitals were turning away emergency patients or evacuating patients and staff. Fortunately, the demand for emergency medical attention and hospital beds did not exceed the capacity of available facilities.

The lack of central communications for hospitals could present a real problem in a future disaster with a greater number of casualties.

RECOVERY

As officials gained control over the immediate life and death issues after the quake, such as search and rescue and fire containment, OES and other agencies turned to the immediate and long-term relief and recovery operations. Aftershocks continued to shake the area, in some cases calling for response efforts after recovery operations had begun.

Despite the magnitude of the damage from the Northridge earthquake, responders shifted quickly and effortlessly from putting out fires to restoring roads; from pulling the dead and injured from collapsed structures to establishing shelters and providing meals; from issuing emergency information to providing housing and financial assistance. Even as aftershocks interrupted the slow return to normal, recovery operations proceeded.

From the State Operations Center in Sacramento and the Regional Emergency Operations Center in Los Alamitos, OES and other state agency officials coordinated the shift to recovery efforts while continuing to maintain response operations as needed. OES called upon its counterparts at the federal level and established the Intergovernmental Liaison Council that operated for months following the event.

OES focused its relief and recovery efforts on the immediate needs of the hundreds of thousands of Southern California residents affected by the temblor.

Shelter and Housing

With more than 13,000 structures damaged and thousands of people homeless in the San Fernando, Simi, and Santa Clarita valleys and in the western sections of Los Angeles and Santa Monica, shelter was an immediate and primary concern. Within hours of the quake, the American Red Cross and the Salvation Army were opening shelters, eventually establishing 49 shelters that housed more than 22,004 people.

One hundred twenty eight mobile feeding units, along with the 47 fixed sites, were set up to serve meals to residents in Los Angeles and Ventura counties. By the end of the third week after the earthquake, over 1.7 million meals had been provided to victims in addition to the thousands of meals provided to emergency responders.

Although numerous emergency shelters were established throughout the impacted area, many people were afraid to enter any building. A Housing Task Force comprised of local, state and federal agencies, the military, the American Red Cross, and the Salvation Army identified parks where shelters could be established. Local jurisdictions and the California National Guard set up tents and other support services that at one point sheltered an additional 20,000 people.

At the peak of operations, more than 10,000 individuals were assigned to the state's emergency operations. Thousands more American Red Cross and Salvation Army volunteers provided care and shelter.

Water Distribution

In large sections of the western San Fernando Valley, the earthquake damaged the water distribution and purification system, leaving hundreds of thousands of people without water. With coordination by OES, a number of private companies donated more than four million gallons of containerized water. The US Army Corps of Engineers delivered a total of 1.7 million gallons of water a day to 30 distribution sites. The CCC helped unload the water and supply it to those in need. This effort continued for 28 days until water supplies had been restored.

POST DISASTER SAFETY ASSESSMENT PROGRAM

The Post Disaster Safety Assessment Program was immediately activated on the morning of the quake and remained operational for approximately two weeks. More than 600 volunteers from the state program and 350 representatives of the U.S. Army Corps of Engineers inspected over 52,000 buildings during the two weeks after the quake.

Volunteers from the Structural Engineers Association of Southern California were assigned to conduct "windshield" surveys to obtain a general sense of where damage was the most acute. By the second day of the survey, volunteers had a good grasp of how extensive the damages were and proceeded to call-up additional volunteers from across the state to help assess damage to individual buildings. Volunteer engineers averaged 12-hour days and donated time worth more than $1.4 million in professional services to the counties of Los Angeles and Ventura. The Corps of Engineers also provided extensive personnel and staff hours in the damage assessment effort.

Emergency Managers Mutual Aid

As a result of the Northridge earthquake, a mutual aid system of emergency services managers and coordinators emerged to assist OES and local jurisdictions in the aftermath of the quake. Patterned after the mutual aid system for fire and law enforcement, the program provided volunteers from cities and counties in a variety of management roles. The state reimbursed travel, per diem, and overtime costs while the volunteer's employer

was asked to absorb regular salary costs. The program worked remarkably well. Managers gained valuable experience in coping with an earthquake, affected jurisdictions received needed assistance, and OES was able to provide a more organized and coordinated response and recovery operation.

Transportation

OES worked closely with Caltrans and the Highway Patrol to deal with transportation problems. While Caltrans began to establish detours and partially open roadways to ease traffic disruption, other transportation agencies developed alternative routes while road repairs were underway. Over one million commuters were affected by damage to the region's transportation system.

Communications

When the Northridge earthquake struck, heavy telephone traffic quickly overloaded phone lines. OES was able to rely upon its OASIS (Operational Area Satellite Information System) satellite communications system to establish communication links with Los Angeles and the REOC at Los Alamitos. OES also installed a transmitter/receiver to communicate in the field with CCC crews and the structural engineering teams conducting damage and safety assessments.

OES and FEMA established a Disaster Field Office (DFO) in Pasadena within three days after the earthquake to coordinate disaster assistance. More than 1,000 local, state and federal employees were assigned to various DFO operations.

At the same time, the first 11 Disaster Application Centers (DACs) opened for business in the disaster area. Eventually 21 fixed DACs and several mobile DACs served the Northridge victims as they sought assistance. The mobile DACs traveled to 80 different locations to serve special populations, some of which were located in isolated communities. A toll-free teleregistration number was established to register applicants, and the California National Guard provided 86 interpreters to assist non-English speaking victims through the disaster application process. When the registration period concluded 12 months after the disaster, more than 680,649 individuals had registered for assistance, more applicants than any other disaster in the nation's history.

Earthquake survivors were provided crisis counseling through Los Angeles and Ventura counties, with partial funding from FEMA and the state.

Temporary Housing

Approximately 34,500 dwelling units in the City of Los Angeles were vacated as a result of earthquake damage, displacing more than 50,000 people. More than 6,000 mobile homes fell off their supports. In many communities, existing vacancies were inadequate to absorb the displaced survivors. To solve this problem, OES created a Housing Task Force with representatives from local governments, state agencies and the federal government, the first-ever attempt in California to create a coordinated response to the housing needs of disaster victims.

In communities where vacancy rates were adequate to absorb the disaster homeless, FEMA provided 19,000 HUD Section 8 housing certificates to relocate the homeless from shelters into interim housing. The Red Cross also gave vouchers for short-term housing. A year and a half after the quake, more than $361,403,556 had been provided for temporary housing assistance to more than 114,000 individuals.

The State Department of Housing and Community Development conducted emergency inspections of mobile homes within days of the quake. The quake had jolted more than 6,000 mobile homes off their foundations, making them uninhabitable. FEMA authorized the repair and placement of mobile units on seismically braced support systems as part of an innovative adaptation of the FEMA Minimal Housing Repair Program.

COORDINATION OF INVOLVEMENT

As part of the overall recovery effort, OES employed extraordinary measures to reach every possible earthquake survivor with information on assistance. The rich diversity of the region's population required the largest outreach effort ever attempted in the United States. OES and FEMA recruited and trained more than 120 field workers to supplement FEMA's 60 permanent workers to distribute information to the affected communities. Bilingual and multilingual staff worked in conjunction with every outreach program, and flyers on disaster programs were translated into nine languages.

Special efforts were made to reach the homebound, elderly, blind and disabled. Outreach teams went to the homes of people who were physically unable to go to the DACs or needed help in seeking other assistance. OES participated in a joint venture with the California Conservation Corps to recruit Volunteers in Service to America (VISTA) to assist in recovery efforts.

Outreach teams received extensive training on disaster assistance programs, the inspection process, social services agencies and their programs, as well as information on earthquake preparedness and hazard mitigation.

DAMAGE REPAIR AND REPLACEMENT

A number of programs exist to provide both temporary and permanent assistance. In addition to the temporary housing program, survivors can apply for grants to help them financially and loans to repair and rebuild their homes and businesses. Money is also available to governmental and non-profit agencies to repair and replace damaged structures and property.

For the Northridge earthquake, FEMA agreed to provide 90 percent of the cost of repair of damaged public structures, with the state reimbursing all of the remaining 10 percent of the repair cost. OES administers this program for FEMA in California. Immediately after the quake, FEMA advanced $200 million to the impacted counties, cities and school districts to expedite repair work and to meet cash flow needs. A preliminary damage assessment later tallied public losses at almost $6.8 billion.

SBA loans to individuals and businesses for repair and rebuilding work rose to $4,015,937 and is expected to go higher as the work continues.

HAZARD MITIGATION

OES activated its Hazard Mitigation Branch within a few hours of the earthquake. This group immediately began to identify opportunities to combine mitigation measures early on in the repair and rebuilding process.

OES worked closely with the California Seismic Safety Commission and the California Department of Conservation, Division of Mines and Geology to establish strategies and priorities for projects to be funded through the hazard mitigation program.

The hazard mitigation branch sponsored workshops for contractors on earthquake repairs and mitigation as well as for homeowners, renters and business owners on low cost mitigation measures they can include in their rebuilding. Total amount made available was $600 million

RECOVERY INSIGHTS

Effectiveness of Recovery Plan

Recovery efforts went according to plan and were, on balance, quite effective. The Individual Assistance programs worked extremely well. The Disaster Application Centers were opened promptly, and both fixed and temporary shelters were set up in short order. More people registered at the DACs and by teleregistration in the first ten days than had registered in the first six months following Hurricane Andrew.

The damage assessment immediately following the quake worked well. The engineering assessments by structural engineers, the California building officials' organization, and OES volunteers, including architects, mobilized quickly and by the end of the first week had inspected several thousand buildings.

Plan Improvement

Some improvement is needed in the system for temporary sheltering. Had the magnitude of the disaster been greater, and more people displaced and without a place to go, the sheltering capability would have been inadequate.

The aspect of recovery that is so complicated, and remains a problem to be resolved, is the disagreement between FEMA and the state and local governments over the extent of damage to individual structures. It is still very difficult and time consuming to do the kind of engineering assessment needed to determine the earthquake's impact on buildings. The complexity of those technical assessments allows for disagreements over issues of eligibility for disaster assistance. This is due, in part, to the fact that federal regulations governing these issues are extremely general and appear to be more applicable to floods and hurricanes than to earthquakes.

More than a year and a half after the Northridge earthquake, there continue to be major disputes between California and the federal government over how California codes and standards should be applied to the repair of damaged facilities.

CONCLUSIONS AND RECOMMENDATIONS

The planning and mutual aid systems and the California Building Code once again proved to be very effective for dealing with a large disaster. The heart and soul of the emergency response system is at the local level, and those local capabilities need to be strengthened whenever possible. Coordination between local and state resources also needs continual fine tuning to insure that response is not delayed due to poor coordination or communications.

It bears repeating that had the earthquake occurred at a different time of day, or on a regular work day, damage would have been much greater.

Emergency managers must continue to improve communications and coordination in anticipation of the next disaster — one that may result in far greater damage and loss to Californians. With the newly adopted Standardized Emergency Management System – and continued vigilance, preparedness, and planning – California will again be ready when disaster strikes.

SECTION V

Northridge Earthquake Insights

Durkin, M.E.,1995, Fatalities, nonfatal injuries, and medical aspects of the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 247-254 .

FATALITIES, NONFATAL INJURIES, AND MEDICAL ASPECTS OF THE NORTHRIDGE EARTHQUAKE

by

Michael E. Durkin[1]

SUMMARY

The Northridge earthquake was directly or indirectly responsible for at least 72 fatalities and thousands of injuries and medical problems.

Structural failure contributed to about one third of the 72 Northridge earthquake fatalities. The performance of nonstructural elements and systems was linked to an additional ten percent. Other causes, ranging from falls to heart attacks, accounted for the remaining sixty percent of the deaths. In this last group 30 heart attack fatalities were classified by the Coroner's office as indirectly earthquake-related.

Nonfatal injuries ranged from crush injuries and heart attacks requiring hospital care to self-treatable cuts and bruises. As many as 11,800 people sought hospital treatment soon after the earthquake causing a sharp increase in injuries treated at emergency rooms. The geographical distribution of both nonfatal injuries and injury severity corresponds to the distribution of earthquake damage and shaking intensity. The bulk of hospital-treated injuries and medical problems were relatively minor, with about ten percent of the injuries or medical problems requiring hospitalization.

Although the health care system in the affected area was disrupted by internal facility damage and external problems such as utility outages, local and regional health resources were sufficient to handle the casualty demand.

FATALITIES DUE TO STRUCTURAL DAMAGE

Although estimates vary, review of available data suggests that 72 people died due to the earthquake (Table 1). Twenty two, or one third of the fatalities, were due directly or indirectly to the collapse of built structures during the earthquake. Of the twenty-two fatalities resulting entirely from structural failure, sixteen perished in the partial collapse of a three-story apartment building; four died in the collapse of three separate wood-frame, single family homes; one reportedly died in a mobile home collapse, and one perished at a collapsed freeway overpass.

Apartment Collapse

The largest loss of life resulted from the collapse of an engineered building located close to the epicenter. Sixteen persons died when the upper portions of the three story Northridge Meadows apartment complex collapsed onto the ground level apartments.

The 164 unit apartment complex consisted of connected buildings surrounding a central area. A two story, reinforced concrete parking structure made up the west edge of the project. These buildings were essentially a "soft-story" wood frame construction. The ground floor perimeter consisted of double and single rows of wood frame garden apartments surrounding a central courtyard. Many of these units were backed, along the exterior edges by carports with steel columns and beams that supported the upper floors. The second and third floors housed apartment units along double loaded corridors.

The earthquake caused the first floor of the apartment complex to collapse in the following manner. The north, south, and east portions of the complex fell approximately ten feet to the north, while the west section collapsed to the south. Twenty-six of the thirty-six ground floor apartments collapsed completely. The remaining ten units did not collapse. All of those killed lived in first-floor apartments in those building areas that completely collapsed. However, not all first floor residents died, because the collapse pattern of the building enabled

[1]Michael E. Durkin and Associates, 22955 Leonora Drive, Woodland Hills, California

some occupants to escape. In a manner typical of building performance observed in other earthquakes, the collapse created void spaces which contributed to the survival of some first floor occupants (Shinobu and others, 1990; Noji and others, 1990; Durkin and others, 1991a). In addition, occupant behavioral patterns contributed to the fatality rate (Durkin and Ohashi, 1989).

Fatalities from Nonstructural Elements

The performance of nonstructural elements and building contents accounted for one tenth of the fatalities. A 28-year old man died of heart failure after sustaining head injuries from being struck by a microwave oven when his mobile home collapsed. Nonstructural elements, including utilities, contributed to an additional six fatalities. Of these six, two were crushed and asphyxiated when buried under hundreds of pounds of books, model trains, and other collectibles in their home. One hospital inpatient and two at home users succumbed when their respirators lost power and stopped. A 25-year old man was electrocuted when he tried to remove a power line from his car.

Table 1. Fatalities by structural type and other causes.

Cause	Fatalities	Percent of Total
Structural Failure		
Buildings		
Wood frame		
Apartment Building Collapse	16	22
Single Family Residential	4	05
Mobile Home		
Mobile Home Collapse	1	01
Other Structures		
Freeways		
Collapsed Freeway Overpass	1	01
Total Related To Structural Failure	**22**	**30**
Nonstructural Elements/ Contents		
Microwave Oven/Heart Attack	1	01
Collectibles	2	03
Respirator Failure	3	04
Electrocution	1	01
Total Related To Nonstructural Elements/Building Contents	**7**	**10**
Other Causes		
Falls	5	07
Automobile Accidents	3	04
Fire	1	01
Suicide	1	01
Exposure	2	03
Heart Attacks	30	42
Total Related To Other Causes	**43**	**60**
Total Fatalities	**72**	**100**

Other causes of Death

Falls contributed to five fatalities. A 49-year old man died when he fell or jumped from the sixth floor window of a downtown Los Angeles hotel. A 74-year old women perished from an aneurysm which ruptured when she fell out of bed during the earthquake. An 88-year old man fell during the earthquake and fractured his hip thus triggering a fatal heart attack. Three others died of a combination of head injuries and heart attacks that the coroner's office determined to be earthquake related. In each case it was unclear whether the fall preceded or followed the heart attack.

Two separate fatal accidents happened at intersections where traffic signals had been disabled by power failures. A third person died when her car overturned after hitting an earthquake caused street break. An earthquake related fire claimed one victim. In this case a 91-year old woman died of smoke inhalation when her mobile home was knocked off support jacks by the earthquake which ruptured a gas line and started a fire.

A 50-year old Ventura County businessman apparently committed suicide when his uninsured business was destroyed by the quake. Two died of exposure.

NONFATAL INJURIES AND MEDICAL PROBLEMS

Health Care Services

The Northridge earthquake was responsible for thousands of injuries and medical problems ranging from crush injuries and heart attacks requiring hospital care to self-treatable cuts and bruises. While we may never know the total health impact of this event, numerous investigations to estimate its specific dimensions are currently underway and in various stages of completion. These studies determine the number, nature, and specific causes of earthquake-related injuries and medical/health care responses to earthquake disaster. Medical studies range from epidemiological research to health service utilization (Johns Hopkins University, 1989; Glass and others, 1977).

Preliminary results from the investigations reveal many different patterns of health service utilization after the earthquake.

1. The Los Angeles County Emergency Operations Center (LAEOC) and the Hospital Council of Southern California, both communicated with Los An-

geles County hospitals periodically to keep a running tabulation of the number of injuries and medical problems that hospitals were treating. Each hospital would attempt to contact the LAEOC at predesignated times to transmit the latest numbers of cases treated.

As of January 22, the LAEOC and the Hospital Council reported that since the earthquake, 7,192 patients had been treated and released from hospital emergency rooms and 1,419 patients had been admitted to hospitals for treatment, for a total of 8,611 non-fatal injuries and medical problems. These surveys did not make a systematic attempt to differentiate between earthquake-related and non-earthquake-related cases.

The surveys did not identify injuries that might have occurred in the neighboring counties of Ventura and Orange.

2. The American Red Cross surveyed southern California hospitals to determine earthquake-related casualty counts. Following Federally declared disasters, the Red Cross has standing agreements with the US Centers for Disease Control to collect basic casualty data, and with local hospitals to supply such data. Within one week of the Northridge event, Red Cross staff began to contact local hospitals in Los Angeles, Ventura, and Orange counties to activate these prior agreements. Each hospital was sent a letter confirming the agreement, a definition of earthquake-related injury or medical problem, and a data recording form for assigning these cases to the following categories: (1) fatality, (2) admitted, (3) treated and released. Reporting was retrospective to the onset of the earthquake. Each hospital was asked to keep a cumulative tally of cases in each category.

   Data was mainly collected through telephone contact with individual hospitals. Normally the Red Cross sends its nurses to review hospital emergency room logs in this type of investigation, but the scope of the relief effort and the large number of hospitals involved stretched available staff to the limits. In some cases, Red Cross staff did visit hospitals and extract results from hospital records. However, in most cases the Red Cross relied on an individual hospital to compile its own results.

   Between January 31 and February 15 (mostly between January 31 and February 6) Red Cross staff collected final earthquake-related casualty categories from participating hospitals, and updated figures already contributed. Although some reporting inconsistan-cies are possible (Hospital A reports all cases up to January 31 while Hospital B reports all cases up to February 6), the Red Cross survey results represent those cases treated during the two week period following the earthquake.

3. Seven Ventura County hospitals reported treating 1,284 injuries and medical problems which was about 11 percent of the three county total and 12 percent of the Los Angeles County cases. As in the San Fernando Valley, treatment was localized. Fifty-one percent of Ventura County's reported hospital treatments took place at Simi Valley facilities, whereas 26 percent of such treatments were in Thousand Oaks.

4. Orange County was apparently spared the numerous casualties of its neighboring counties. The six responding Orange County hospitals reported treating only four earthquake-related injuries or medical problems.

Analysis of Red Cross Data

Preliminary analysis of Red Cross data from the 102 Los Angeles, Ventura and Orange county hospitals shows a total of 11,846 non-fatal casualties treated (Table 2). Of the total number, 10,802 cases were treated and released; 1,044 cases required hospital admission.

The Los Angeles county hospital count by geographic area illustrates the areal distribution of treatment.

Table 2. Geographical (spatial) distribution of hospital-treated injuries and medical problems.

Areas	Hospitals	Admitted to hospital	Treated and released	Total
Los Angeles County	89	1,032	9,526	10,558
West San Fernando Valley	9	504	5,434	5,938
East San Fernando	9	406	2,877	3,283
Hollywood	4	34	141	175
Central Los Angeles	10	9	145	154
San Gabriel Valley	15	20	85	105
West Los Angeles.	6	18	121	139
Santa Monica	2	11	131	142
South Bay	12	21	351	372
Long Beach	7	4	92	96
Southeast Los Angeles	15	5	149	154
Ventura County	7	10	1,274	1,284
Orange County	6	2	2	4
Total	102	1,044	10,802	11,846

Source: Preliminary analysis of hospital emergency room data from the Northridge earthquake survey, Durkin Associates.

Because this was the area of most intense shaking and heaviest damage, San Fernando Valley hospitals treated 5,938 (78 percent of the total cases), the largest number of cases, because most of the injuries occurred in the epicentral area. The West San Fernando Valley hospitals treated more than half of these cases. Northridge medical facilities treated 34 percent of the total West Valley cases. Santa Monica hospitals reported treating relatively few casualties even though this community was heavily damaged.

Most earthquake injuries and medical problems were not severe enough to require hospitalization. The overall ratio of non-hospitalized to hospitalized treatments was about ten to one in the three county area.

The distribution of injury severity appears to correspond to areas of shaking intensity and relative damage. About 90 percent of the cases requiring hospitalization were treated at San Fernando Valley hospitals. Less than one percent of hospitalization cases were treated at Ventura County hospitals.

Several geographic areas (Hollywood, West Los Angeles, and the San Gabriel Valley) had hospitalized to non-hospitalized ratios of greater than 1 in 10. This higher ratio might result from hospitals in less damaged areas receiving patients from crowded hospitals or from people voluntarily seeking these hospitals.

Limitations of Red Cross Hospital Survey

Potential limitations are (1) the lack of uniform training of individual hospital workers in data collection methods (for example, a hospital might report all cases treated within a particular time period, completely disregarding the earthquake-related definition); (2) emergency room records may lack sufficient detail to determine if an injury was related to the earthquake; (3) the lengthy Red Cross updating process (between January 31 and February 15) might cause an under reporting of the actual case numbers and skew the case distribution among hospitals (for example, an early reporting hospital would miss any patients treated after the final report was submitted, whereas a late reporting hospital would include these late arriving cases); and (4) the Red Cross data do not provide a day-by-day breakdown of patient volume to show when hospital services were most heavily utilized.

Despite its limitations, the Red Cross data are useful for a preliminary look at the frequency and areal distribution of "earthquake-related casualties" within the three county area.

Comparison of Pre-and Post-earthquake Emergency Room Cases

Another way to estimate the impact of Northridge earthquake on health services is to compare use of certain health care system units before and after the earthquake. Beginning on January 21, LA County Public Health Workers, as part of a standard communicable disease surveillance program, began reviewing emergency room (ER) logs at 15 San Fernando Valley emergency rooms. The team reviewed emergency room records for the three week period between January 10 and January 30 (one week before the earthquake and two weeks after the event). For each day, in this interval, they tabulated the number of injuries, infectious diseases, and other medical conditions treated in each ER (Los Angeles County Department of Health Services, 1994).

Preliminary analysis yielded the following three important results:

(1) immediately after the earthquake, the subject emergency rooms experienced a substantial increase in the volume of services rendered as evidenced in overall patient visits. In the seven days before the earthquake, patient visits were at a steady range of between 700 and 800 visits per day. However, on January 17, the overall number of patient visits jumped three-fold to about 2,300;

(2) immediately after the event, ERs treated more injuries as opposed to other types of medical problems. Soft tissue and orthopedic trauma, such as lacerations and fractures, averaged about 120 per day during the pre-earthquake period. On the day of the earthquake, the number of this type of injury treated increased tenfold to 1,500. The volume of injury-related cases seen dropped to 500 per day on January 18, and to 250 per day on January 19. Over the next ten days, this rate gradually tapered off bringing the injury rate to slightly above the pre-quake rate by January 30;

(3) about one week after the earthquake, emergency room visits by patients with gastroenteritis increased. Infectious diseases averaged about 80 per day during the week before the earthquake. They remained at the same level for the first six days after the quake. However, the infectious disease rate jumped from 80 to 200 per day on January 23, due mostly to gastroenteritis cases, but returned to the pre-earthquake rate the next day.

TYPES OF EARTHQUAKE-RELATED INJURIES AND MEDICAL PROBLEMS

The distribution, by general type, of injuries and medical problems seen by area emergency rooms immediately after the earthquake is shown in Table 3. This table provides a percentage breakdown showing the relative proportion of six major injury and illness groups seen at five major hospitals located in or close to the most heavily damaged areas. These figures are derived from records of the emergency rooms at five acute-care general hospitals for the first twenty-four hours after the earthquake. Hospital A is a private hospital located near the earthquake epicenter in the west San Fernando Valley. Hospital B is a private hospital located in west Los Angeles. Hospital C, also a private hospital, is situated in an area of heavy damage in Santa Monica. Hospital D is a public hospital in the east San Fernando Valley. The fifth hospital (Hospital E) is a public hospital just east of downtown Los Angeles. The percentages presented in Table 3 are derived from a preliminary analysis of cases seen at the emergency room of each hospital during the twenty-four hour period following the earthquake.

This analysis shows that soft tissue and orthopedic injuries including lacerations, contusions, burns, sprains, and fractures formed the overwhelming majority of the immediate cases treated at four of the five hospitals studied.

Such injuries comprised 61 percent of all cases treated at the five hospital emergency rooms. The percentage of soft tissue and orthopedic injuries treated at each hospital ranged from 49 to 75 percent at the five hospitals.

Cardiovascular conditions such as chest pain, dysrhythmia, hypertension, and full cardiac arrest made up 10 percent of the total cases. Neurological and psychiatric complaints like anxiety and seizure constituted 5 percent of the cases. Respiratory problems (specifically asthma, toxic inhalation and respiratory infection) were also responsible for 5 percent of the complaints. Gastrointestinal problems was seven percent. Obstetrics and gynecological episodes (namely threatened abortion, pre-term labor, and labor) comprised 3 percent of the events. Other medical problems such as replacing lost medication or simply lacking sufficient detail to assign the case to a particular category make up one percent of the total. One hospital had insufficient data in emergency room records to categorize an additional fifty-five cases by type.

Table 3. Distribution, by general type, of all injuries and medical problems treated at five hospital emergency rooms for first 24 hours after earthquake.

Injury or Medical Problem Groups	Hospital A N=204		Hospital B N=60		Hospital C N=103		Hospital D N=96		Hospital E N=165		All Cases N=628	
	N	%	N	%	N	%	N	%	N	%	N	%
Soft Tissue/Orthopedic	133	65	45	75	66	64	56	58	81	49	381	61
Cardiovascular	2	1	8	13	14	14	13	14	25	15	62	10
Neuro/Psychiatric	2	1	5	8	2	2	6	6	16	10	31	5
Respiratory	4	2	0	0	7	7	9	9	12	7	32	5
Gastrointestinal	8	4	1	2	8	8	0	0	27	16	44	7
OB/GYN	0	0	1	2	3	3	12	13	2	1	18	3
Other	0	0	0	0	3	3	0	0	2	1	5	1
Insufficient Data*	55	27	0	0	0	0	0	0	0	0	55	9
TOTAL	**204**	**100**	**60**	**100**	**103**	**101**	**96**	**100**	**165**	**99**	**628**	**101**

Source: Preliminary analysis of hospital emergency room data from the Northridge earthquake by Durkin Associates.
* Emergency room records were insufficient to categorize these medical problems.

Soft Tissue and Orthopedic Injuries

Soft Tissue and Orthopedic injuries constituted the bulk of injuries treated at the five hospital emergency rooms; therefore, we further analyzed the 381 injuries treated in these five settings and found the following: (1) lacerations made up 52 percent of the total, (2) 22 percent were sprains and shoulder dislocations made up another 2 percent, (3) fractures accounted for 14 percent of the soft tissue and orthopedic injuries, and (4) contusions made up 10 percent of the injuries. Only one burn injury was treated at the five hospitals during the twenty-four hour study interval, even though numerous fires occurred after the earthquake.

Caseloads Related to Earthquake

Review of the emergency room records in four of the five hospitals revealed that the earthquake-relatedness cases varied among injury categories. Ninety-five percent of the Soft Tissue and Orthopedic, 97 percent of the Cardiovascular, and 83 percent of the Neuropsychiatric cases were potentially earthquake-related. Only 14 percent of Gastrointestinal and 11 percent of the Respiratory problems were potentially related to the earthquake. About 53 percent of the OB/GYN and 60 percent of the Other conditions were not earthquake-related.

EMERGENCY HEALTH CARE INSIGHTS

Previous earthquake studies offer valuable insights about the number, areal (geographical) distribution, and type of injuries and medical problems treated after earthquakes, as well as demands placed on area hospitals and their emergency rooms. However, the results of hospital emergency room assessments, by themselves, provide an incomplete picture of overall casualty patterns. First, such studies do not encompass the total range of organizational settings such as hospital outpatient units, physician's offices, and clinics, where injuries and medical problems are commonly treated in an earthquake's aftermath. In a recent study of the Loma Prieta earthquake, work-related injuries were found to be 60 percent of the cases treated in nonhospital-based settings or were self-treated.

Although serious casualties requiring hospital admission would normally be reflected in hospital surveys, the Northridge hospitalized caseload only comprise about 10 percent. Even though these investigations yield important information about the volume of medical services rendered, they do not reveal which injuries and medical problems were earthquake-related. Most hospital records, especially those completed immediately after a disaster, lack sufficient detail to determine whether or not the medical condition was earthquake related or to document and evaluate the risk factors contributing to the casualty.

Building Damage

The Northridge earthquake caused considerable damage to health facilities and significant health service disruption. Immediately after the shaking stopped, structural and nonstructural damage forced several hospitals to evacuate patients. Non-critical patients were discharged, critical patients were transferred to other facilities, and the hospital staffs prepared to receive incoming casualties. Structural damage to several older medical buildings caused a reduction in operations or closure.

Nonstructural damage to utilities was a pervasive source of disruption. Some facilities were left without power or water. Ironically, structural and/or nonstructural damage forced three hospitals that had been rebuilt or repaired after the 1971 San Fernando earthquake to close for extended periods of time.

Because southern California has extensive health care resources, the health care units in the disaster area were sufficient to handle the immediate demand.

Fatal Injuries

The Northridge earthquake casualty patterns are similar to those observed in the 1971 San Fernando and 1989 Loma Prieta earthquakes. First, there were relatively few fatalities in each event. The Northridge earthquake caused 72 fatalities (42 if heart attacks are excluded), the San Fernando earthquake caused 67 deaths (NOAA, 1973), and the Loma Prieta earthquake resulted in 63 deaths (Durkin and others, 1991b). Second, the fatality rates were similar and relatively low when compared with earthquakes worldwide. The gross fatality rate for the Northridge event was 5.5 deaths per 100,000 population. The fatality rate for the San Fernando earthquake was 5.2 per 100,000. The fatality rate for Loma Prieta was 1.3 per 100,000 population. Excluding heart attacks from this analysis yields fatality rates of 3.2, 4.5, and 1.3 per 100,000 population for Northridge, San Fernando, and Loma Prieta, respectively (The Earthquake Project, 1993). Third, the fatalities related to structural performance occurred in a small number of damaged structures. For instance, the collapse of buildings in the Northridge Meadows apartment complex accounted for 16 of the 22 (or 72 percent) of the Northridge collapse related deaths. Forty seven of the 58 (or 81 percent) San Fernando earthquake deaths happened in the collapse of buildings at the Veteran's Administration San Fernando Hospital. Fourth, 42 of the 57 (or 73 percent) Loma Prieta deaths related to structural failure took place in the Cypress Viaduct collapse.

Nonfatal Injuries

Nonfatal injury patterns were also similar in that, in each case, injuries were widespread but relatively minor. For instance, the crude hospitalization rate for hospital-treated injuries appears to be about 10 percent for Northridge, 8 percent for San Fernando, and 17.5 percent for Loma Prieta (The Earthquake Project, 1993) .

Life Safety Elements

The preliminary study supports the following findings from research on injuries in earthquakes worldwide:

(1) geotechnical performance, independent of and coupled with building performance contributed to earthquake-related mortality and morbidity; (2) built structures other than buildings, in this case a freeway overpass and streets, posed a serious life safety threat; (3) occupant contact with nonstructural elements and building contents is a major source of minor injuries but is associated with few serious injuries (Durkin and others, 1994); and (4) occupant actions and behavior patterns can play an important role in injury occurrence and prevention (Murakami and Durkin, 1989).

One important distinction of the Northridge earthquake is that many fatalities were concentrated in the collapse of "soft-story," predominately, wood frame structures rather than reinforced concrete structures – the site of most San Fernando and Loma Prieta deaths. This finding, along with the poor seismic performance of other similar structures, suggests the need to include "soft-story" building type in earthquake hazard reduction activities, and to incorporate resulting casualty coefficients in earthquake casualty estimations.

Earthquake Injury Prevention

What insight do these preliminary observations give? The principal factors are pre-earthquake rehabilitation of known hazardous structural and nonstructural components of buildings, the provision of adequate health care facilities after an earthquake, and training in earthquake awareness and self-help actions to avoid serious injury during and immediately after an earthquake. Ongoing casualty mitigation measures include the long term rehabilitation of earthquake damaged facilities and the restoration of health care services to their pre-earthquake state (Durkin and Thiel, 1992).

The major "demand-side" mitigation actions include: (1) improving hazard identification, urban design, and site planning procedures; (2) developing improved seismic building codes and code enforcement practices; (3) designing and implementing better pre-earthquake retrofit and post-earthquake repair practices for existing buildings; (4) training building occupants in appropriate response; and (5) identifying and prioritizing the relative risk of potentially hazardous nonstructural elements and building contents (Durkin and others, 1994).

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the National Science Foundation (supplement to NSF Grant No BCS-9216881), and the U.S. Geological Survey (USGS Grant No 1434-95-6-2590). We also thank the American Red Cross, the Los Angeles County Department of Health Services, Northridge Hospital Medical Center and Century City Hospital for their continuing collaboration and participation in this ongoing research.

REFERENCES

Durkin, Michael E., Coulson, Anne, Hijar, Martha, Kraus, Jess, and Ohashi,Hitomi , 1991, The survival of people in collapsed buildings, Disaster Chronicles No. 3, Earthquake In Mexico, September 19 and 20, 1985: Panamerican Health Organization, Washington, D.C.

Durkin, Michael E. and Ohashi, Hitomi, 1989, Casualties, survival and entrapment in heavily damaged buildings: Proceedings Of The Ninth World Conference On Earthquake Engineering, Maruzen Co., Ltd.,Kyoto, and Tokyo, Japan.

Durkin, Michael E. and Thiel, Charles C., Jr., 1992, Improving measures to reduce earthquake casualties: Earthquake Spectra, v. 8, no. 1.

Durkin, M.E., Thiel, C.C., Schneider, J.E., and De Vried, T., 1991b, Injuries and emergency medical response in the Loma Prieta earthquake: Bulletin of the Seismological Society of America, v. 81, no. 5, p. 2143-2166.

Durkin, M.E., Thiel, C.C., and Schneider, J.E., 1994, Casualties and emergency medical response *in* The Loma Prieta, California, Earthquake of October 17, 1989 – Loss Estimation and Procedures: U.S. Geological Survey Professional Paper 1553-A, p. A9 - A38.

Glass, R.I., Urrutia, J.J.,Sibony, S., Smith, H., Garcia, B. and Rizzo, L., 1977, Earthquake injuries related to housing in a Guatemalan Village: Science, v. 197, p. 638-643.

Johns Hopkins University, 1989, Proceedings, International Workshop On Earthquake Injury Epidemiology For Mitigation And Response: The Johns Hopkins University, July 10-12, Baltimore, Maryland.

Los Angeles County Department of Health Services, 1994, Hospital Emergency Room Survey, January 10 - January 30, 1994: Los Angeles County, Department of Health Services, Disease Control Programs.

Murakami, Hitomi.O., and Durkin, Michael E., 1989. Studies of occupant behavior In earthquakes - review and perspectives: Proceedings of The Ninth World Conference on Earthquake Engineering, v. VII, p. 681-686.

National Oceanic and Atmospheric Administration, 1973, Individual and Organizational Dimensions, in San Fernando, California Earthquake of February 9, 1971: U.S. Department of Commerce, NOAA, p. 261-291.

Noji, E.K., Armenian, H.K., Oganessian, A.P., 1990, Case-control study of injuries due to earthquake in Soviet Armenia, Annals of Emergency Medicine, Summary List Of Structures With Demolition Orders: Office of the Baguio City Engineer, v. 19, p. 449.

PAHO, 1991, Earthquake In Mexico, September 19 and 20, 1985, Disaster Chronicles, No. 3: Panamerican Health Organization, Washington, D.C.

Shinobu, S., Coburn, A., and Spence, R., 1990, Human casualties in building collapse, Literature Review: The Martin Center for Architectural and Urban Studies, University of Cambridge, England:

The Earthquake Project, 1993, The Loma Prieta earthquake – impact on local emergency medical services and patient care: Department of Public Health, Emergency Medical Services Agency, City and County of San Francisco.

Tierney, K., 1995, Social aspects of the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 255-262.

SOCIAL ASPECTS OF THE NORTHRIDGE EARTHQUAKE

by
Kathleen Tierney[1]

INTRODUCTION

By any standard, the Northridge earthquake was one of the most costly and damaging disasters in U. S. history. When all the claims are finally processed, the costs of repairing earthquake damage and providing relief to victims are expected to exceed $20 billion. The assistance effort launched after the Northridge earthquake was the largest ever undertaken for a U. S. disaster; in the four month period following the earthquake, approximately 556,000 applications for assistance were filed by community residents and business proprietors who suffered earthquake–related losses. Up until that time, the previous high for applications received was 304,000 for Hurricane Hugo in 1989, which included victims in the states of North and South Carolina, Puerto Rico, and the U. S. Virgin Islands.

The number of disaster–related claims filed and the amounts disbursed through various disaster assistance programs have been truly unprecedented. As of the end of October, 1994, the Federal Emergency Management Agency (FEMA) had received 519,000 applications for disaster housing assistance and had issued approximately 430,000 checks totaling $1.86 billion. Approximately 179,600 households had applied to the U. S. Small Business Administration (SBA) for loans to cover home repairs; of this number, about 88,300 loans had been approved, and $2.2 billion in loan funds had been disbursed to homeowners. Nearly 300,000 households had applied for FEMA's Individual and Family Grant program, which provides aid to households that do not qualify for disaster assistance loan programs. About 51,200 businesses had applied for SBA loans to cover direct earthquake damage or the losses associated with business interruption, and $1.32 billion in loans had been paid out. The earthquake did extensive damage to public buildings, roads and bridges, and water control facilities; as of the end of October, $1.86 billion had been obligated to cover the cost of earthquake–related repairs to publicly–owned facilities (statistics provided by Governor's Office of Emergency Services). Claims continue to be processed, and it will be a long time – probably years if not a decade or more–before all the costs associated with the earthquake are known.

Along with other highly-damaging U. S. events like Hurricane Andrew and the 1993 Midwest floods, Northridge vividly demonstrates the vulnerability of the built environment and human populations to disasters. The earthquake affected so many and caused such high losses in part because it struck in the heart of a highly urbanized area. The 1990 population of Los Angeles County is estimated at about 8.8 million, of whom 3.5 million live in the City of Los Angeles. The size of the building and infrastructure inventory in the impact region is enormous. In contrast, the 1992 Landers–Big Bear events were larger in magnitude than Northridge, but they caused relatively little property damage and social disruption, because they occurred away from major population centers. Although the 1989 Loma Prieta earthquake did extensive damage in densely populated parts of the Bay Area, the epicenter and area of most intense damage was in Santa Cruz County, 75 miles from San Francisco.

Northridge underscores the point that even moderate–sized earthquakes can do tremendous damage and place severe demands on emergency response and relief organizations when they occur in areas where there is a high concentration of population and structures at risk. As a result of the Northridge event, both scientists and policymakers are coming to a new appreciation of the costliness and disruptiveness of urban earthquakes, and loss estimates for future southern California events are in the process of being revised upward. The devastating consequences of the January 17, 1995 earthquake in Kobe, Japan further highlights the vulnerability that exists in urban areas that are subject to the earthquake hazard and the great importance of earthquake loss reduction.

[1]Disaster Research Center, University of Delaware, Newark, Delaware

This discussion contains general observations on what is known at this point about the social aspects and impacts of the earthquake. There are a number of social science investigations under way that, when completed, will provide much more detailed information in a number of key research areas (see discussion below on ongoing projects). Preliminary observations on the social and emergency management aspects of the earthquake have been presented in several other publications, including reconnaissance reports by the Earthquake Engineering Research Institute (1994; and 1995, in press), the National Center for Earthquake Engineering Research (1994), and the Governor's Office of Emergency Services (1994). The City of Los Angeles has also produced a highly informative account of earthquake impacts and the governmental response in that jurisdiction (City of Los Angeles, 1995).

This report first discusses the ways in which the societal response to the Northridge event resembles patterns seen in other earthquakes and in disasters in general. It then discusses new issues that were raised by this earthquake event.

DISASTER RESPONSE PATTERNS

Since shortly after the Second World War, social scientists have been conducting research on social and organizational response patterns in disaster situations (for a summary of this work see Drabek, 1986). The literature includes data on a range of community and organizational types and on both natural and technological disasters. Much of the human and organizational behavior that was observed in the aftermath of the Northridge event was consistent with the patterns researchers have documented in other major U. S. disasters, and in many ways the immediate response following the earthquake mirrors what has been observed, albeit on a smaller scale, in other recent California earthquakes.

Public Response – Adaptive and Altruistic

Many fictional and media accounts characterize the public's behavior in disaster situations as generally negative and problematic. For example, community residents are commonly described as panicking in the aftermath of major disasters, or, conversely, as too shocked and dazed to be capable of helping themselves. The period following disaster impact is characterized as a socially chaotic time when strict law enforcement and other social controls are necessary to prevent outbreaks of looting and other anti– social behavior. Empirical studies on disaster–stricken communities and on the public's response in major disasters paint a contrasting picture—one that documents an increase in altruism, a decline in anti–social behavior, and high levels of responsiveness and self–help among victimized populations.

The public's response following the Northridge earthquake was consistent with this pattern. Immediately after the event, community residents spontaneously helped one another, and many people volunteered to assist those needing help. Material and financial donations poured into the stricken area, and even those who suffered losses in the earthquake offered help to those they considered worse off. Criminal activity dropped throughout the affected region, even in relatively undamaged areas. For example, in the 24–hour period following the earthquake, the Los Angeles Police arrested only 73 people, while the usual average is around 550.

At the Northridge Meadows apartment complex, where the collapse of part of the first floor of one of the buildings killed 16 people and left a number of victims trapped, initial search and rescue activities were conducted not by officially–designated agencies, but rather by other apartment residents and neighborhood volunteers. By the time fire and rescue teams arrived, as many as 180 occupants had already gotten out of the building on their own or with the aid of their neighbors. This pattern of spontaneous altruism and self–help, which occurred throughout the region during the post–impact period, is similar to what has been observed in other major earthquake events, such as the 1985 Mexico City earthquake and the 1989 Loma Prieta event (O'Brien and Mileti, 1993; Wenger and James, 1994).

Similarly, while the media focused on the provision of emergency shelter to earthquake victims by agencies such as the Red Cross, a far greater number of those who were displaced by the earthquake were given a temporary place to live by neighbors, relatives, and friends. For example, data on 421,101 households that had applied to the Federal Emergency Management Agency for assistance as of late April 1994 indicated that, of the approximately 88,000 who had not yet returned to their damaged homes at the time they applied, nearly 57,000 reported they were living with friends or family members.

Studies on other community emergencies have noted that the widespread desire to help during the emergency response period can create problems for governmental and other response agencies that are unprepared to handle the large convergence of volunteers and resources that typically occurs when disaster strikes (Fritz and Mathewson, 1957). Even when resources are needed and have been requested, convergence creates major management problems, and excessive convergence can actually interfere with response activities. Although emergency responders who were on duty when the Northridge earthquake occurred initially had to cope on

their own, personnel, resources, and volunteers began pouring into the impact area almost immediately. Rather than being forced to manage the emergency with insufficient resources, within a very short time the major challenge many response agencies faced was trying to effectively deploy and manage the immense volume of human and material resources that had become available.

Preference for Outdoor Shelter

The day after the earthquake, Los Angeles officials estimated there were approximately 20,000 people citywide who were sleeping in tents and other makeshift shelters in front yards, parks, parking lots, and other open spaces. When official shelters were opened in schools and other facilities, many people were still reluctant to seek shelter indoors. This pattern of informal outdoor sheltering was also observed in other recent California earthquakes, notably the Whittier Narrows and Loma Prieta events. In many cases, people felt safer outdoors because of their fear of aftershocks; concern about the structural safety of dwellings was also a major factor. As in other recent California events, Latinos, particularly Mexican and Central American immigrants, tended to feel safer in informal outdoor shelters.

Officials were concerned about threats to the health and safety of disaster victims in makeshift shelters. Recalling conflicts involving informal shelter arrangements that developed in Watsonville following the Loma Prieta earthquake, Los Angeles and other communities strongly resisted the sanctioning of unofficial shelters and the distribution of family–sized tents to those who were staying outdoors. However, within a few days after the earthquake, a decision was made to begin distributing larger tents for those wishing to shelter outdoors. Beginning on the day after the earthquake, a major organized effort was launched to encourage people to go back into their homes, to indoor shelters, or into outdoor, tented "refuge centers" (some adjacent to shelter facilities) that were established to serve those who were still too fearful to stay indoors. In Los Angeles, this effort involved the formation of "reassurance teams," consisting of health, mental health, parks and recreation, building and safety, and Red Cross personnel, as well as members of the clergy, that systematically canvassed informal encampments around the city in the days following the earthquake.

Impact of Prior Experience and Planning

When a major disaster occurs, affected communities must establish working relationships with state and federal response and relief agencies. Disaster experience can help local communities anticipate what will be needed when another disaster strikes and can contribute to improvements in emergency preparedness. The social science literature suggests that prior disaster experience can be an important factor that influences communities and organizations to place more emphasis on disaster preparedness and response and to incorporate the lessons they learned in previous disasters into their emergency operations (Drabek, 1986).

The Northridge earthquake demonstrates the impact that prior disaster experience can have on a community's ability to function successfully under emergency conditions. For example, the emergency management system in the City of Los Angeles had faced several major crises prior to the earthquake. The 1992 civil unrest and the trials subsequently conducted in connection with the Rodney King case and the civil disturbance itself required public safety agencies like the Los Angeles Fire and Police Departments to step up their emergency planning and training activities. The size of the Los Angeles City emergency operations center (EOC) was nearly doubled following the 1992 disturbances, and since the earthquake the facility has been reconfigured and upgraded. Because changes had been made as a result of recent experience, the EOC functioned as an interagency facility following the earthquake to a much greater degree than it had during the 1992 emergency. The wildfires that occurred in the fall of 1993 provided another important test of the emergency response system. The fact that the City and County of Los Angeles had been involved in several federally–declared disasters (including the civil unrest, the 1993 fires, and major floods) in the years immediately prior to the earthquake made the process of coordinating outside emergency and relief assistance smoother. At the time the earthquake struck, the State of California and the Federal Emergency Management Agency were already operating a Disaster Field Office in Pasadena as part of the wildfire disaster assistance effort. Those offices became the hub for emergency operations following the Northridge event.

In contrast, because some of the communities affected by the Northridge earthquake had less recent disaster experience (or, in a few cases, none at all) they had not had the same opportunity to review organizational performance in light of an actual event and to make adjustments in their operations.

Prior research has also shown that engaging in disaster preparedness planning activities helps communities respond better when disasters occur (Kartez and Lindell, 1987, 1990; Kreps, 1991). Although no disaster plan covers all possible contingencies, a good disaster plan outlines the framework for the overall response, assigns responsibilities for the performance of disaster–related tasks, and helps responding agencies, organiza-

tions, and jurisdictions better understand their disaster–related roles and relationships. Equally importantly, the planning process itself tends to improve the level of interorganizational and interjurisdictional understanding, enhancing the potential for coordination among different organizations and levels of government.

In the case of the City of Los Angeles, the City's earlier experience with the 1971 San Fernando earthquake was a major factor that influenced its commitment to earthquake hazard reduction, including earthquake–specific emergency planning. In addition to having an emergency operations organization that had been in existence for over ten years and that had functioned in several recent crises, the City also had a well–developed emergency operations plan and an earthquake recovery plan that was in final draft form at the time the earthquake struck. This emphasis on pre–disaster planning, coupled with extensive disaster experience, were significant factors in the City's ability to manage the emergency.

The southern California region is generally well–prepared for earthquakes. Nevertheless, communities in the impact region varied in the extent to which they had plans in place for earthquakes and other disasters at the time the earthquake occurred. Emergency organizations in less well–prepared communities appear to have had more difficulty handling response–related tasks, such as setting up emergency operations centers, requesting and obtaining mutual aid resources, damage assessment and the production of damage records, and coordination with county, state, and Federal agencies. Less well–prepared and less–experienced communities were less knowledgeable about the intergovernmental emergency response system and the types of assistance that are made available under a disaster declaration. While some jurisdictions understood how disaster operations are organized under the Federal Response Plan, others did not. In short, disaster planning activities, emergency exercises, and actual disaster experience help familiarize response agencies with emergency procedures, and communities and organizations that were deficient in one or more of these areas generally had more difficulty responding than those that were better prepared.

NEW ISSUES RAISED BY THE NORTHRIDGE EARTHQUAKE

In addition to providing support for much of what social scientists already know about the public, organizational, and community response in disaster situations, the earthquake also brought a number of new issues to light. Among these are questions about the impact of newly–developed emergency management strategies and technological innovations on the emergency response, the problem of "earthquake ghost towns," and the use of Federal mitigation funds during the disaster recovery period.

New Emergency Management Strategies and Technologies

Although the activities of emergency response organizations following earthquakes and other disasters have been studied extensively in the past, relatively few studies have dealt with the organizational and governmental response in recent U. S. earthquakes. Recent social scientific studies on the post–earthquake organizational response have tended to focus on specific components of the emergency response system, such as hospitals and emergency medical service providers (see, for example, Pointer and others, 1992; Thiel and others, 1992), or on particular types of organizations, such as those that provide lifeline services (Tierney, 1992). The largest recent organizational and governmental response study was conducted not on a U. S. event, but rather on the 1985 Mexico City earthquake (Dynes, Quarantelli, and Wenger, 1990).

More research on the organizational and community response in disaster situations is needed, in part because new management strategies and technologies are now being employed. The Northridge earthquake is a case in point. With respect to organizational innovations, the State of California recently adopted an emergency response organizational framework called the Standardized Emergency Management System (SEMS), which is designed to facilitate the coordination of emergency response activities. SEMS is based on another widely–disseminated organizational and interorganizational response model, originally developed in California, known as the incident command system (ICS). Under recent legislation, local jurisdictions in California were required to move toward the adoption of the SEMS framework in their planning and response activities. At the time of the earthquake, many communities, including Los Angeles, had already begun using SEMS. The Northridge earthquake provides an opportunity to assess how SEMS, ICS, interorganizational and interjurisdictional mutual aid agreements, and other approaches to crisis management functioned in a major earthquake and to document the lessons learned.

A new response framework has also been evolving at the Federal level. For approximately the last eight years, the Federal Emergency Management Agency (FEMA) and other Federal agencies have been developing a Federal Response Plan (FRP), which is designed to coordinate the activities of 27 key emergency response agencies (26 Federal agencies and the American Red Cross) and mobilize resources in a catastrophic event. The Federal government was heavily criticized for its slow-

ness in responding to Hurricane Andrew in 1992 (National Academy of Public Administration, 1993). Following that event, increased emphasis was placed on improving the FRP, making participating Federal agencies more aware of their roles, and enhancing the capacity of FEMA and other Federal agencies to respond in a rapid and "proactive" fashion to the impact or threat of a disaster. The FRP was fully implemented in the Northridge event, and Federal aid was mobilized on a massive scale. The earthquake thus provides a setting for understanding which aspects of the Federal response worked well and which still need improvement.

Like the organizational innovations described above, technological change has also altered the manner in which U. S. disasters are managed. Emergency personnel now have wide access to communications equipment, decision aids, and data bases that were virtually unknown even ten years ago. The new technologies that were used extensively in Northridge include computers, cellular telephones, pagers, fax machines, geographic information system (GIS) data bases, satellite communications, and teleconferencing.

The use of GIS technology was particularly notable following the Northridge event. Although GIS was also used during the emergency response and recovery phases in other major U. S. disasters, including Hurricane Andrew and the 1993 Midwest floods, GIS was used much earlier and for a broader range of applications in the Northridge event. For example, at the Disaster Field Office in Pasadena, which was one of the major centers where Federal and State agencies coordinated their response and relief activities, a GIS unit, set up within days of the earthquake, recorded damage information, made loss projections, and compiled maps showing earthquake shaking intensities, locations of emergency shelters and disaster assistance application centers, the distribution of red, yellow, and green–tagged structures, and other types of information.

Immediately following the earthquake, the Governor's Office of Emergency Services asked EQE, Inc., a firm that had a consulting agreement with OES, to use its GIS–based EPEDAT (Early Post–earthquake Damage Assessment Tool) system to develop initial loss estimates. These early estimates formed the basis for the State's request for Federal assistance and for the Congressional aid appropriation that followed (see Goltz, 1994 for a more detailed discussion of this process). During the early recovery period, GIS was also being used to track the recovery process and to develop priorities for the use of Federal funds that are available for post–earthquake mitigation projects. It is important to understand how GIS and other new technologies affect the management of disasters, particularly since their use is sure to become more widespread.

Earthquake "Ghost Towns"

The earthquake produced many pockets of heavy residential and commercial damage, and some neighborhoods were so hard–hit that they could become permanently blighted areas. In the City of Los Angeles, where the problem is most evident, there are 38 census tracts in which 100 or more housing units were destroyed. In 13 tracts, 12 of which are located in the San Fernando Valley, more than 15 percent of the total available housing units have been lost (*Los Angeles Times*, May 3, 1994). In September, 1994, nine months after the earthquake, the *Los Angeles Times* reported that repairs had not begun in more than half of the severely damaged properties in these "earthquake ghost towns," and that as many as one–quarter of the owners of ghost town properties had no plans to rebuild (*Los Angeles Times*, September 18, 1994).

Delays in repairs and reconstruction are attributable in part to the fact that Los Angeles area property values had been declining for several years. Many landlords were saddled with heavy debts even before the earthquake, and some could not afford to make repairs. Others had yet to receive the loans they had applied for. Still others were planning to allow their properties to go into foreclosure.

Concern began to grow among city officials and the public that, unless remedial action was taken, the concentration of vacant and damaged structures in earthquake ghost towns inevitably would result in a cascade of problems: poor sanitation, debris build–up, untended yards, declining property values, squatters in abandoned buildings, safety and security problems, and an increase in crime, drug use, and prostitution.

In spring 1994, city government began developing a strategy to ameliorate problems of earthquake–generated blight through such measures as the provision of low–interest loans to finance repair and reconstruction projects in designated ghost-town areas. Rebuilding programs would be funded by federal Community Development Block Grants, Federal funds made available for housing repairs, and bonds issued by the City of Los Angeles (*Los Angeles Times*, May 4, 1994). The U. S. Small Business Administration, which provides loans to owners of disaster–damaged residential and business property, also agreed to review thousands of disaster loan applications that had previously been denied and to give special priority to loan applications involving ghost town properties (*Los Angeles Times*, June 29, 1994). It will be important for researchers to track the ghost town problem over time and to assess the effectiveness of the strategies that were developed to ameliorate it.

Post–Earthquake Mitigation Programs

The Stafford Act, the legislation under which disaster assistance monies are made available in Federally–declared disasters, also provides for the allocation of funds specifically earmarked for projects to mitigate future disaster losses. The amount of money made available for mitigation may total 15 percent of the total disaster assistance allocation, provided state matching funds are available. Because of the extraordinarily high losses following Northridge, the pool of money available for mitigation projects could be as large as $800 million.

The State of California and local jurisdictions in the impact area face major opportunities and challenges in devising cost–effective ways to expend these funds. Even though the amount available from the Federal government for mitigation could be substantial, a myriad of useful projects could be undertaken with that money. The State thus needed to decide how to use those funds and how to prioritize mitigation projects. After holding a series of meetings and workshops on potential uses of the funds in the mitigation pool, it was decided that the money could best be used to mitigate nonstructural hazards in the schools.

California's budget crisis may ultimately limit its access to mitigation monies. A bond issue to generate funds to offset the State's share of disaster assistance and recovery costs was defeated by voters in June 1994, and at the time this report is being written, the State is having difficulty raising the necessary matching funds.

Even if access to mitigation monies is ultimately limited by California's fiscal problems, significant mitigation projects will still be undertaken with both public and private funding. During the recovery period following earthquakes and other disasters, tensions always develop between the need to "build back" and to "build better," between the need for rapid restoration and reconstruction and the need to avert future risks. The manner in which mitigation issues are being addressed following the Northridge earthquake and the cost–effectiveness of mitigation measures that are adopted are topics that merit further study.

ONGOING RESEARCH ON SOCIAL ASPECTS

Policies and programs to reduce earthquake losses must be informed by a thorough understanding of how and why those losses occur. Social science research currently being undertaken on the Northridge earthquake will undoubtedly make a major contribution to that knowledge base. In an effort to ensure that the lessons of Northridge are well–documented, the National Science Foundation (NSF) made funds available in mid–1994 for research on a range of scientific and engineering topics, including studies on the social and organizational aspects of the disaster. Social science projects sponsored under the Northridge earthquake initiative include studies on residents' responses immediately after earthquake impact, how the earthquake affected small businesses, the impact of the earthquake on households, housing loss and reconstruction, and earthquake recovery in ghost towns and other hard–hit neighborhoods. Table 1 is a complete listing of new NSF–sponsored projects and investigators. In addition to these projects, which were funded under a special initiative, several social science investigators with ongoing NSF projects obtained supplementary funding to conduct research on the Northridge event.

A number of other studies on the socioeconomic aspects and impacts of the earthquake are currently being conducted with funding from other sources, including the National Center for Earthquake Engineering Research and the U. S. government's Centers for Disease Prevention and Control. Preliminary findings from these studies should begin becoming available in 1995.

CONCLUSIONS

The tremendous loss of life, damage, and societal disruption caused by the recent Kobe earthquake are grim reminders of what earthquakes can do when they strike in close proximity to highly urbanized areas. The Northridge earthquake and the Kobe event that occurred exactly one year later underscore the urgency and importance of containing not only the physical damage earthquakes cause, but also the human suffering and negative social impacts they engender. Earthquake events are natural occurrences, but earthquake–related losses are in large measure the result of social processes and activities—such as land use and development patterns, building practices and code adoption and enforcement, and individual, organizational, and governmental choices regarding hazard mitigation and emergency preparedness—that affect the extent to which people and property are placed at risk.

Combating the earthquake problem requires both an in-depth understanding of those social processes and the translation of this understanding into effective action programs. This is what social scientists who study earthquakes are attempting to accomplish, and research on the Northridge event should result in progress toward that goal.

Table 1. NSF-sponsored projects on socioeconomic impacts and societal response.

Alesch, Daniel	University of Wisconsin–Madison	Effects of the Northridge Earthquake on Small Business Survival: Causes and Prevention of Small Business Failure Due to Earthquakes
Arnold, Christopher	Building Systems Development, Inc.	Building Damage, Business Interruption and Recovery: The Northridge Fashion Center and Chamber of Commerce
Bolin, Robert	New Mexico State University	Organizational Responses and Household Recovery Following the Northridge Earthquake
Bourque, Linda	University of California–Los Angeles	Community Responses to the Northridge Earthquake
Comerio, Mary	University of California–Berkeley	The Impact of Housing Losses in the Northridge Earthquake: Recovery and Reconstruction Issues
French, Steven	Georgia Institute of Technology	Damage from the 1994 Northridge Earthquake in Light of Planning Since the 1971 San Fernando Earthquake
Gatz, Margaret	University of Southern California	Multi–Generational Predictors of Earthquake Impact and Preparedness
Gordon, Peter	University of Southern California	Business Interrruption in the Northridge Earthquake
Lindell, Michael	Michigan State University	Hazardous Materials in the Northridge Earthquake: Hazard Analysis, Mitigation and Preparedness
Mader, George	Spangle Associates	Evaluation of Los Angeles's Organization & Plan for Recovery and Reconstruction
Nigg, Joanne	University of Delaware	Emergency Response and Early Recovery Activities in the Northridge Earthquake
Olshansky, Robert	University of Illinois Urbana–Champaign	Land Use Planning for Seismic Mitigation: Lessons From Los Angeles
Olson, Robert	VSP Associates	Hospital Evacuation in the Northridge Earthquake
Perkins, Jeanne	Association of Bay Area Governments	Test of a Model of Housing Damage in Earthquakes and Resulting Mass Care Needs in the Northridge Earthquake
Rose, Adam	Pennsylvania State University	Economic Impact of the Northridge Earthquake
Scawthorn, Charles	EQE International, Inc.	Analysis of Insured Losses in the Northridge Earthquake
Stallings, Robert	University of Southern California	Neighborhood Retention Following the Northridge Earthquake

ACKNOWLEDGMENT

Partial support for the compilation of this report was provided by National Science Foundation Grant No. CMS–9415738, "Emergency Response and Early Recovery Activities in the Northridge earthquake." The views presented here are those of the author.

REFERENCES

City of Los Angeles, 1995, In the wake of the quake – A prepared city responds, Report to the Los Angeles City Council: Office of the Mayor and Ad Hoc Committee on Earthquake Recovery, Los Angeles.

Drabek, T. E., 1986, Human system responses to disaster – An inventory of sociological findings: Springer–Verlag, New York.

Dynes, R.R., Quarantelli, E.L., and Wenger, D., 1990, Individual and organizational response to the 1985 earthquake in Mexico City, Mexico: Disaster Research Center, Book and Monograph Series No. 24, University of Delaware, Newark, Delaware.

Earthquake Engineering Research Institute, 1994, Northridge earthquake, January 17, 1994 – Preliminary reconnaissance report, Hall, John F., Technical Editor: Earthquake Engineering Research Institute, Oakland, California.

Earthquake Engineering Research Institute, 1995, Earthquake Spectra, special issue on the Northridge earthquake, Hall, John F., Technical Editor: Earthquake Engineering Research Institute, Oakland, California (in press).

Fritz, C.E. and Mathewson, J.H., 1957, Convergence behavior in disasters, National Research Council Disaster Study No. 9: National Academy of Sciences, Washington, D.C..

Goltz, J.D., 1994, Summary report: Utilization of new technologies in the Northridge, California, earthquake of January 17, 1994, Draft Project Report: EQE Engineering and Design, Irvine, California.

Governor's Office of Emergency Services, 1994, Northridge earthquake, January 17, 1994: Interim Report, Sacramento, California.

Kartez, J.D., and Lindell, M.K., 1987, Planning for uncertainty – The case of local planning: Journal of the American Planning Association, v. 53, p. 487–498.

Kartez, J.D. and Lindell, M.K., 1990, Adaptive planning for community disaster response *in* Sylves, R.T., and Waugh, W.L., eds., Cities and Disaster – North American Studies in Emergency Management: Charles C. Thomas, Springfield, Illinois, p. 5-31.

Kreps, G.A., 1991, Organizing for emergency management *in* Drabek, T.E., and Hoetmer, G.J., eds., Emergency Management – Principles and Practices for Local Government: International Management Association, Washington, D.C.

Los Angeles Times, 1994, LA plans cash infusion to revive quake ghost towns, May 3, p. A1, A16.

Los Angeles Times, 1994, Staving off the ghosts of January 17, May4, p. B6.

Los Angeles Times, 1994, SBA acts to remedy quake ghost towns, June 29, p. B1, B8.

Los Angeles Times, 1994,2nd wave of quake destruction, September 18, p. A1, A16–17.

National Academy of Public Administration, 1993, Coping with catastrophe – Building an emergency management system to meet people's needs in natural and manmade disasters, Report to the United States Congress and the Federal Emergency Management Agency: National Academy of Public Administration, Washington, D.C.

National Center for Earthquake Engineering Research, 1994, General reconnaissance report, Goltz, J.D., ed., Technical Report NCEER-94-005: State University of New York at Buffalo, New York.

O'Brien, P.W., and Mileti, D.S., 1993, Citizen participation in the emergency response *in* Bolton, P., ed., The Loma Prieta, California, earthquake of October 17, 1989 – Public Response: U.S. Geological Survey Professional Paper 1553–B, p. B23–B30.

Pointer, J.E., Michaelis, J., Saunders, C., Martchenke, J., Barton, C., Palafox, J., Kleinrock, M., and Calabro, J.J., 1992, The 1989 Loma Prieta earthquake – Impact on hospital and patient care: Annals of Emergency Medicine, v. 21, p.73–78.

Thiel, C.C., Schneider, J.E., Hiatt, D., and Durkin, M.E., 1992, The 9–1–1 EMS process in the Loma Prieta earthquake: Prehospital and Disaster Medicine, v. 7, p. 348–358.

Tierney, K.J., 1992, Organizational features of U. S. lifeline systems and their relevance for disaster management *in* Proceedings of the 4th U. S.–Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems: National Institute of Standards and Technology Special Publication 840, Washington, D.C.

Wenger, D.E. and James. T.F., 1994, The convergence of volunteers in a consensus crisis – The case of the 1985 Mexico City earthquake *in* Dynes, R.R., and Tierney, K.J., eds., Disasters, Collective Behavior, and Social Organization: University of Delaware Press, Newark, Delaware, p. 229–243.

Romero, P.J. and Adams, J.L., 1995, Economic impact of the Northridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 263-271.

ECONOMIC IMPACT OF THE NORTHRIDGE EARTHQUAKE

by

Philip J. Romero[1] and Justin L. Adams[2]

EXECUTIVE SUMMARY

The Governor's Office of Emergency Services (OES) estimates total structural and property damage from the Northridge quake at between $18 and $20 billion, making this the nation's second costliest disaster (Hurricane Andrew ranks first). Over 112,000 structures were damaged across 2,129 square miles throughout Los Angeles, Ventura, and Orange counties. Damage was roughly evenly split among residential, commercial, and government uses.

Slightly more than $2 billion of federal aid grants has been spent. Additionally, southern California residents submitted approximately $7.2 billion in insurance claims. Assuming that Californians bear 17% of the federal costs of disaster relief and that 50% of insurance claims are paid out by non-California firms, then outside aid totals between $5.5 and $12.7 billion. That leaves a shortfall of $6.8 to $16.0 billion that Californians must make up.

In the immediate aftermath journalists and commentators tended to extremes in their assessments of the quake's long-run economic impacts. Two myths emerged: "apocalypse" and "boom."

The pessimists, who were the preponderant majority, expected the quake's severe property and infrastructure damage would cause massive economic dislocations that would destroy business and consumer confidence in the region.

Alternatively, optimists assumed that the infusions of money to repair buildings and infrastructure would kickstart the construction industry and greatly accelerate the region's economic recovery.

In reality neither extreme (apocalypse nor boom) occurred. Money spent on rebuilding stimulated a region mired in recession and likely accelerated California's economic recovery by two to four months. But because vast resources were diverted towards *replacing* and *repairing* homes, businesses, and infrastructure rather than used in producing goods and services, the state on the whole would have been better off had the quake never happened.

This fact would have been apparent to anyone who had reviewed California's last great quake in a populated area: the 1989 Loma Prieta earthquake. Loma Prieta's economic dislocations were relatively minor and concentrated in the short-term. For the region as a whole virtually any measure of economic activity–retail sales, employment, or home prices–showed at most a slight dip for 2-3 months before returning to trend.

This is not because local residents received so much outside aid that they were held harmless; locals bore roughly half of the burden of damage repair (the other half came from insurance payments and outside aid). Instead residents got the money to rebuild by dipping into their future consumption.

The Loma Prieta analogy implies that Northridge rebuilding would occur quickly, with most economic indicators recovering within a few months. Because of the bonus from construction spending, the region would see a brief stimulus during the rebuilding period, to be later followed by slightly depressed economic activity (relative to a no-quake baseline) for one to two years as residents financed the shortfall by reducing their future consumption.

[1]Chief Economist, Governor's Office, Sacramento, California
[2]Research Fellow, Governor's Office of Planning and Research, Sacramento, California

Assuming that the Northridge shortfall (the difference between total economic losses and outside aid) will be financed by area residents over two years following a post-quake construction spike lasting roughly nine months, then Los Angeles area consumer spending will be depressed between 0.3 and 1.0% from a no-quake baseline. This could cost 20-60,000 jobs. These are quite small compared to the six million employed in the L.A. area.

In other words, the quake probably accelerated the onset of L.A.'s economic recovery by a few months. However, this came at a price: that recovery will be slightly less pronounced than if no quake had occurred.

The quick recovery of business and consumer confidence was due in large part to the swift action taken by emergency response teams and state, local, and federal agencies. Had it not, the doomsayers' predictions might have been borne out. Nowhere was government's ability to deliver the goods quickly and imaginatively more visible than in the state's rapid reopening of the freeways.

In short, it now appears that the quake caused a very brief disruption, followed by a surge in activity as a result of outside aid and rebuilding. Over the longer term economic activity will be slightly below the without-quake trend as residents pay for the initial rebuilding. The magnitude, in percentage terms, was bound to be modest in an area with an economy that is larger than all but a dozen countries.

But the pessimists could have been right. The innovative and timely measures implemented by state and local agencies may well have made the difference between the Northridge quake's actual, modest effects and the economic tragedy that might have been[3].

DIRECT IMPACTS

Immediate Physical Damage

The Northridge earthquake rocked the Los Angeles area during the early morning hours of January 17, 1994. Centered in the San Fernando Valley, the quake measured 6.8 on the Richter scale causing widespread damage throughout the region. The Northridge quake is particularly noteworthy for two reasons: its location in a densely populated area and its violent upward thrusting, unlike the side-to-side shaking typical of California earthquakes.

Fortunately, the immediate loss of life was slight, because the quake struck in the pre-dawn hours on a holiday. Physical damage, however, was enormous. The Governor's Office of Emergency Services (OES) estimates total structural and property damage at between $18 and $20 billion, making this the nation's second costliest disaster (Hurricane Andrew ranks first). Over 112,000 structures were damaged across 2,129 square miles throughout Los Angeles, Ventura, and Orange counties. Damage was roughly evenly split among residential, commercial, and government uses.

Severe damage to sections of five major freeways (including Interstate 10, the busiest freeway in the nation) and interchanges increased some commute times by as much as 300% and isolated several communities. Assuming (conservatively) that dislocations caused $500 million in lost productivity and $1 billion of lost output in the region, the true direct cost of the Northridge earthquake stands between $19.5 and $21.5 billion.

Outside Aid

Soon after the quake Congress approved the Clinton Administration's Earthquake Aid Appropriation of $11.2 billion, which set aside money for repairing freeways, roads and infrastructure, as well as for assisting households and small businesses. By September, the Federal Emergency Management Agency (FEMA) and OES had received over 620,000 applications for state and federal assistance, more than twice the previous record.

As indicated in Table 1, slightly more than $2 billion of federal aid grants has either been obligated or spent since January 1994. This aid encompasses short-term residential repairs and rental housing expenses, infrastructure repairs, last-resort grants through the Individual Family Grant Program, and crisis counseling. Another $3.5 billion in loans have been approved by the Small Business Administration.

Additionally, southern California residents submitted approximately $7.2 billion in insurance claims as of November. Assuming that Californians bear 17% of the federal costs of disaster relief and that 50% of insurance claims are paid out by non-California firms, then outside aid totals between $5.5 and $12.7 billion. That leaves a shortfall of $6.8 to $16.0 billion that Californians must make up.

[3] Information in this paper is current as of November 1994.

Table 1. Outside compensation to southern California earthquake victims

Appropriated	Obligated		Non-Calif. Share*	
$11.2 B	$1.070 B	Housing		
	1.062 B	Infrastructure		
	.152 B	IFGP**		
	.035 B	Counseling		
	$2.319 B		83%	$1.924 B
	$3.471 B	SBA Loans	N/A	N/A
$7.2 B	$7.2 B	Private Insurance	50%	$3.6 B

*Refers to the amount of outside aid not funded by California dollars. California taxpayers, for instance, are responsible for approximately 17% of Federal tax revenue, and therefore the balance can be thought of as new money for the State.
**Individual Family Grant Program.

LONGER-TERM IMPACTS

Myths About the Effects of Natural Disasters

In the immediate aftermath journalists and commentators tended to extremes in their assessments of the quake's long-run economic impacts. Two myths emerged: "apocalypse" vs. an economic "boom."

Apocalypse - The pessimists, who were the preponderant majority, expected the quake's severe property and infrastructure damage would cause massive economic dislocations that would destroy business and consumer confidence in the region. This would lead to a substantial emigration of businesses and consumers, further weakening an economy already weighed down by over three years of recession. John Berry of the Washington Post, for example, wrote of the quake's "psychological trauma" and the fear that the quake "...may be the sort of straw-that-broke-the-camel's-back event that convinces many already skeptical people that southern California is simply not a place in which to live or do business" (January 18, 1994, p. A12).

Such forecasts–and there were many–were wrong for three reasons. First, they presumed that residents and businesses in earthquake-prone regions are nevertheless surprised that earthquakes occur. In other words, residents are myopic about the possibility of disasters and the consequent economic disruptions. Second, it presupposes that all of the losses will be paid for out of local economic activity, when in fact losses will be spread across the nation. And third, it assumes that all rebuilding will be done quickly and at full price—in effect treating the loss of physical capital *stock* as if it were a decline in income *flow*.

Boom - This less common myth assumed that the infusions of money to repair buildings and infrastructure would kickstart the construction industry and greatly accelerate the region's economic recovery. The recovery would be further aided by increased retail sales to replace damaged property. In its extreme form the region's positive ripples could reach nationwide. An illustrative *Los Angeles Times* article was headlined "Earthquake may have spurred growth as billions were spent to rebuild," in reference to the nation's actual first quarter GDP being four-tenths of one percent higher than previous expectations (May 28, 1994, p. D4).

While it is true that money spent on construction has more indirect economic impact than that spent on consumer goods, the "bonus" is just 15% to 25% (i.e. the multiplier for the construction industry is only 1.15 to 1.25 times the average multiplier for the economy as a whole). For a true boom to occur, the additional bang-for-the-buck would need to be substantially larger.

Early projections of the Northridge quake's economic impact tended to mirror these dichotomous mythic views of apocalypse and boom. Not surprisingly, the farther away analysts were from Northridge (and the less they knew about actual damage in the Los Angeles area), the more dire their predictions became. Three examples from the first few weeks after the quake:

- The UCLA Business Forecast predicted short-lived job losses followed by four quarters of modest job growth, higher retail sales and lower unemployment. Overall, the quake would have a small but negative impact on the Los Angeles region.
- The WEFA Group (1994), based in Bala Cynwyd, Pennsylvania, projectedthe quake could cost the *nation* 0.5 percentage points (annualized) of real GDP growth in the first quarter (about $8.4 billion) and 0.4 percentage points of personal consumption (about $4.6 billion). WEFA anticipated that these indices would receive a sizeable boost in the medium-term, but in the long-term the quake would have a small but negative impact on the nation.
- DRI/McGraw Hill (1994), located in Lexington, Massachusetts, acknowledged that there would be modest gains in the construction and retail industries in the short-run. However, the long-run would witness substantial outmigration as the quake aggravated falling consumer confidence from the recession.

In reality neither extreme (apocalypse nor boom) occurred, a fact that would have been apparent to anyone who had reviewed California's last great quake – the 1989 Loma Prieta earthquake – in a populated area.

Learning from the Loma Prieta Experience

The quake, measuring 7.1 on the Richter scale, struck the San Francisco Bay area just before the evening rush hour on October 17, 1989 and caused over $7 billion of damage. Loma Prieta's economic dislocations were relatively minor and concentrated in the short-term (Association of Bay Area Governments, 1991). For the region as a whole virtually any measure of economic activity–retail sales, employment, home prices,–showed at most a slight dip for 2-3 months before returning to trend. Home prices, for example, were back to their pre-quake levels by January 1990, after dipping 1.9%.

This is not because local residents received so much outside aid that they were held harmless: locals bore roughly half of the burden of damage repair (the other half came from insurance payments and outside aid). Instead residents got the money to rebuild by dipping into their future consumption.

An examination of trends in regional retail sales will illustrate. Comparing actual sales to an estimate of their trend without the quake reveals that they fell by 2.2% in the fourth quarter of 1989 (the quake occurred near the beginning of the quarter), but were 27.6% above trend in the first quarter of 1990 (and were 3.5% above the last pre-quake quarter). This spike amounted to $3.9 billion in retail sales.

Thereafter retail sales averaged 2.5% below the pre-quake trend; by the end of 1991 (two years after the quake) cumulative depressed sales equalled the first quarter 1990 spike. However, this overstates the effect of the quake somewhat since the region went into recession in late 1990.

In short, there was no great boom nor bust: Bay area residents nullified the impact of the quake almost immediately (within 2-3 months) by borrowing from their next one to two years of consumption.

Discrepancies Between Theory and Experience

There are two main methods of predicting the long-term impact of a natural disaster: rely on a past analogy, or make theoretical calculations using traditional regional input-output methods. Many analysts prefer the analogy approach since it is difficult to accurately incorporate the timing of cash infusions. Regional input-output methods typically assume instantaneous cash flows and thus tend to overstate the economic effects caused by disasters, leading to the extreme predictions cited above.

Take Loma Prieta as an example. The Bay Area suffered $7 billion of damage, receiving during the three-month reconstruction phase $3.5 billion in outside aid. Assuming that construction multipliers yielded 22.1 jobs for every million dollars spent, then the input-output approach implies that 77,350 more jobs were created during reconstruction compared to a no-quake baseline.

In actuality, employment numbers suggest that quake reconstruction created an average of 1.4% more jobs relative to a no-quake baseline, or in other words only about 42,500 additional jobs. Thus the input-output approach overstates job creation by about 82%.

Given that damage from the Northridge quake was about three times the size as that of Loma Prieta, we expect that input-output overestimate would be correspondingly larger. Consequently, our analysis below emphasizes the "analogy" approach, but includes brief elaborations based on the theoretical approach.

IMPLICATIONS OF THE NORTHRIDGE QUAKE'S ECONOMIC EFFECTS

Primary Effects

As summarized on Table 2, damage plus lost output and productivity totals between $19.5 and $21.5 billion. Assuming that 50% of insurance payouts come from out of state and that Californians bear 17% of the funding for outside aid, then Californians would be required to make up a shortfall of $6.8 to $16.0 billion.

Table 2. Outside assistance to southern California—a balance sheet

Assets: Obligated	Assets: Actual	Liabilities
$9.296 B (Federal Aid)	$1.925 B (Federal Aid)	$18-20 B (Damage)
$3.6 B (Private Ins.)	$3.6 B (Private Ins.)	$1.0 B (Lost Output)
		$0.5 B (Lost Productivity)
$12.696 B	$5.525 B	$19.5-21.5 B
Shortfall:	**$6.8-16.0 B**	

The Loma Prieta analogy would imply that Northridge rebuilding would occur quickly, with most economic indicators recovering within a few months. Because of the bonus from construction spending, the region

would see a brief stimulus during the rebuilding period, to be later followed by slightly depressed economic activity (relative to a no-quake baseline) for one to two years as residents financed the shortfall by reducing their future consumption.

It should be noted, however, that the Los Angeles area economy differs greatly from the Bay area's. The Los Angeles economy is roughly twice the size of the Bay area's. For instance, 1990 taxable sales and personal income in Los Angeles were $145 billion and $327 billion, respectively, compared to $69.5 billion and $164 billion, respectively, in the Bay area. The Los Angeles economy was weathering a severe regional recession, with a declining manufacturing sector and decreasing defense employment. Most of the 9.3% of the California labor force unemployed in January were located in the south. By contrast, the Bay area had not yet entered recession when the Loma Prieta quake hit. Thus Loma Prieta's lessons cannot be applied exactly to Northridge.

Assuming that the Northridge shortfall (the difference between total economic losses and outside aid) will be financed by area residents over two years following a post-quake construction spike lasting roughly nine months, then Los Angeles area consumer spending will be depressed between 0.3 and 1.0% from a no-quake baseline. This could cost 20-60,000 jobs. These are quite small compared to the six million employed in the Los Angeles area.

Table 3 shows the direct and indirect effect of these job gains and losses on employment versus the "no-quake" trend. Small short term job losses (10 to 30,000) would be followed by modest job gains (20 to 40,000) for most of a year resulting from a construction stimulus. The next one to two years would see modest job losses (20 to 60,000) given the financing of reconstruction.

Table 3. Northridge earthquake job impacts

Change in Area Employment			
Period	Jobs	%Change	Reason
1-2 months	-10 to 30,000	-.15 to .46%	Dislocation Phase
3-12 months	+20 to 40,000	+.31 to .62%	Rebuild Phase
12-24 months	-20 to 60,000	-.31 to .93%	Financing Phase

These area-wide numbers mask local effects which could have been proportionately somewhat higher in more isolated regions, like the Santa Clarita Valley. However, the rapid repair of the freeway system minimized these effects.

Importance of Rapid Infrastructure Repair

One prerequisite for the return to normalcy after a major earthquake is the repair of infrastructure. Water and electricity must be restored and roads must be repaired so that residents can return to work, factories can produce, and goods can be shipped. The faster this occurs, the smaller the region's economic dislocations including lost output and lost productivity.

As a result of swift action by emergency response teams and state, local, and federal agencies, business and consumer confidence bounced back very quickly. Had it not, the doomsayers' predictions might have been borne out. Nowhere was government's ability to deliver the goods quickly and imaginatively more visible than in the state's rapid reopening of the freeways.

The extensive network of roads and freeways in the Los Angeles area are the region's transportation and commercial lifelines. Consequently, many analysts predicted devastating economic consequences shortly after the Northridge quake because of the severe damage inflicted on five major L.A. area freeways and freeway interchanges. One casualty, Interstate 10, carries more commuter traffic than any other in the nation while another, Interstate 5, serves as California's primary north-south shipping artery. Further, entire communities literally became isolated with the collapse of certain interchanges.

The speed of freeway repairs clearly dictated how large the quake's impact on the economy would be. The Office of Planning and Research estimated that each day of these freeway closures cost California $2.5 million in lost productivity, $940,000 in lost output, and $200,000 in wasted fuel due to increased travel times and queuing. Initially, freeway repairs were expected to take as much as two years.

However, because of the innovative incentive approach implemented by state officials and CalTrans, the final freeway repairs were completed in early November, months ahead of schedule. Under contracts reached with individual construction firms, CalTrans agreed to pay monetary bonuses for each day of early project completion and contractors agreed to pay CalTrans for each day of delay. While similar incentive schemes have been used in other public works projects, this was by far the largest public sector project to utilize incentives in California. The early completions saved Californians almost $150 million net of payments to contractors.

Other Estimates and Recent Evidence

The empirical data appears generally to show the pattern we have asserted – short-term dislocation followed by a rebuilding stimulus followed by slightly depressed activity.

Take taxable sales as an example. Figure 1 presents three different projections of taxable sales in California based on data from the UCLA Business Forecasting Project. The December 1993 forecast essentially shows expected taxable sales growth, absent the quake. From the first quarter of 1994 through 1995, average annualized taxable sales were forecast to increase by approximately 4.8%.

The March 1994 forecast represents the immediate post-quake outlook. Employment and personal income data from January and February showed very short-lived quake dislocations, and analysts expected infusions of outside aid to be sizeable. Consequently, taxable sales projections were revised upward, accounting for the expenditures on rebuilding that would soon follow, to annualized average growth rates of 5.4%.

September's forecast shows a more precise picture of what happened to taxable sales in the first two quarters of 1994. Actual taxable sales fell below pre-quake levels in Q1 1994 and inched back above them in Q2. The divergence from the March forecast most likely resulted from better estimates of damage and of how little outside aid was received in southern California. Although there is no discernible spike during the rebuilding phase, taxable sales are projected to quickly rebound, remaining below the pre-quake baseline until the second quarter of 1995.

One surprise is that taxable sales projections overtake the pre-quake baseline so soon after the quake. Two important points should be noted, however. First, these rosy scenarios can be partly attributed to California's current economic recovery, which has been stronger than the pre-quake forecast anticipated. Second, rather than being specific to the Los Angeles area our data is for all of California. While the Los Angeles area represents about 40% to 50% of California's economy, these aggregate numbers dilute the quake's greater local economic impacts.

Figures 2 and 3 show snapshots of economic activity through a number of indices, including personal income, construction employment and median home prices. Figure 2 presents four different forecasts for the second quarter of 1994, or the reconstruction phase, relative to a no-quake baseline. As expected, employment is typically higher and median home prices remain strong, although new residential construction is down sharply. Surprisingly, personal income did not receive a huge blow.

Figure 3 presents a longer-term scenario, comparing forecasts for the fourth quarter of 1994, during the financing phase. Relative to a no-quake baseline the projections show stronger employment, with fewer construction jobs, as Southern California finishes reconstruction and the state continues its economic recovery. Home prices are higher, but this may be correlated with the drop in new residential construction. Personal income growth remains steady.

Other evidence seems to support our hypotheses. In early October, Dun & Bradstreet (D&B) published a report on the Northridge earthquake's economic impact on the Los Angeles area. D&B (1994) cited the "remarkably quick" rebuilding of the Los Angeles transportation system as one of the three key reasons why "the Los Angeles Economy has done an extraordinarily effective job of coping with the aftermath of the Northridge earthquake."

Rather than find a cascade of business failures brought on by financial hardship, they discovered that the L.A. economy is currently *stronger* than it was before the quake. The rate of business failures located within 40 miles of the quake's epicenter continued to drop through 1994, often by as much as 50%. Additionally, those businesses within 20 miles of the epicenter (177,000 firms employing 1.6 million workers) experienced failure rates that were shrinking slightly faster than the statewide rate.

Longer Term Consequences

There has been no evidence of business outmigration from California as a result of the Northridge quake. While there were a very few highly-publicized stories of businesses leaving, perhaps a few hundred jobs were lost from the area. Many firms that did leave relocated to other parts of California.

Of more concern is the "outmigration" of the insurance industry and the effect this could have on California's housing market, a critical piece of the State's economic rebound. The California Department of State and Consumer Services notes that the quake caused many insurance providers to stop offering new policies. As it stands now, 85% of the market for new homeowners policies has been shut down.

This is not because huge insurance losses ($7.2 billion) are bankrupting many firms. In fact, no insurance provider has gone out of business as a result of the quake, and only one (20th Century, California's ninth-largest insurer) has been placed under regulatory order to exit the State's homeowners market entirely over three years.

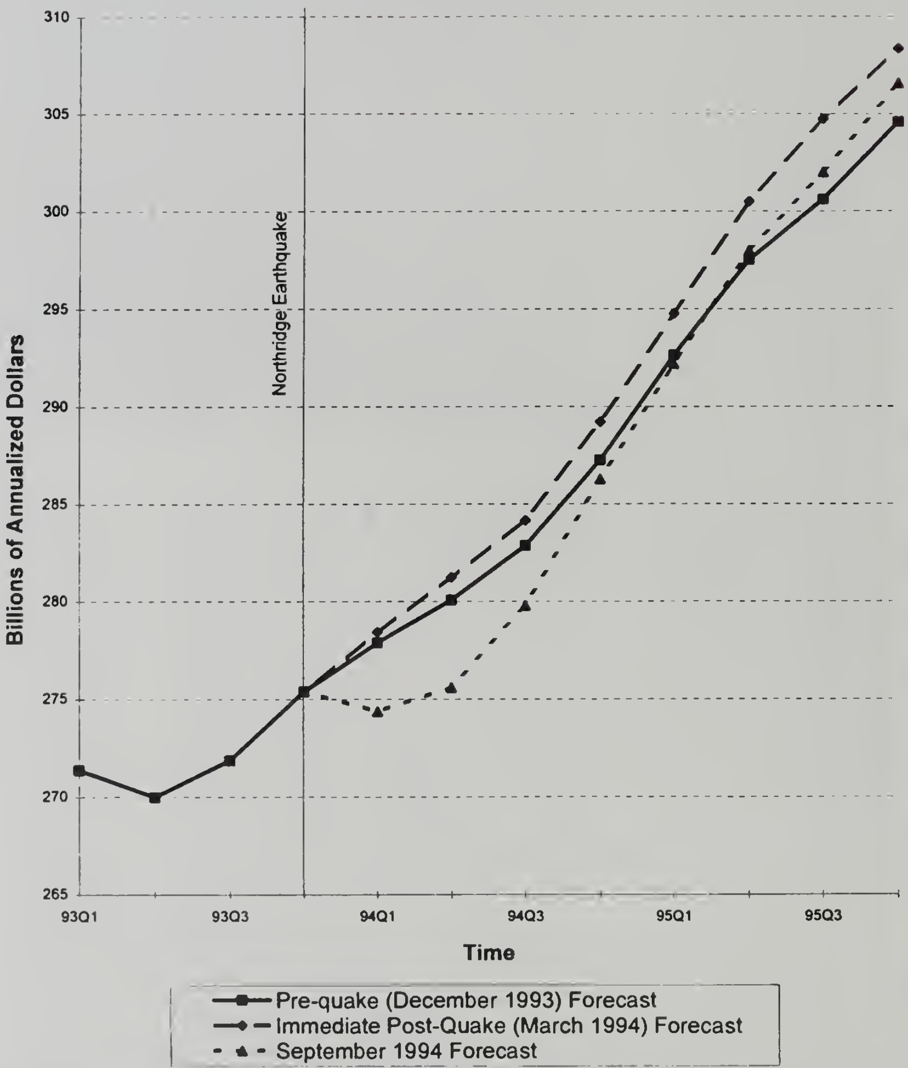


Figure 1. How the Northridge earthquake affected California: Taxable sales forecasts based on UCLA Business Forecasting Project data.

	Forecast from December 1993	Forecast from Merch 1994	Forecast from June 1994	Forecast from September 1994
Personel Income (In Billions)	$671.4	$692.6	$685.9	$684.7
Percent Change	-	3.16%	2.16%	1.98%
Taxeble Sales (In Billions)	$281.1	$279.0	$277.0	$275.6
Percent Chenge	-	-0.75%	-1.46%	-1.96%
Unemployment Rete (%)	10.1	9.4	9	9.8
Percent Change	-	-6.93%	-10.89%	-12.87%
Construction Employment (In Thousands)	468	451	452	463
Percent Change	-	-3.63%	-3.42%	-1.07%
Residential Building Permits (In Thous. Units)	120	125	95	99
Percent Change	-	4.17%	-20.83%	-17.50%
Retail Trede Employment (In Thousands)	2746	2765	2772	2829
Percent Change	-	0.69%	0.95%	3.02%
Medien Home Price (In Thousends)	$181.1	$185.4	$186.8	$200.1
Percent Change	-	2.37%	3.15%	10.49%
Manufecturing Employment (In Thousands)	1742	1759	1755	1772
Percent Chenge	-	0.98%	0.75%	1.72%

Figure 2. Economic projections for California for the second quarter, 1994 (percent changes vs. December 1993 forecast). Based on UCLA Business Forecasting Project.

	Forecast from December 1993	Forecast from March 1994	Forecest from June 1994	Forecast from September 1994
Personel Income (In Billions)	$680.7	$704.1	$698.8	$695.5
Percent Change	-	3.44%	2.66%	2.17%
Taxable Sales (In Billions)	$288.3	$286.9	$285.3	$286.3
Percent Change	-	-0.49%	-1.04%	-0.69%
Unemployment Rate (%)	9.8	9.1	8.3	8.8
Percent Change	-	-7.14%	-15.31%	-10.20%
Construction Employment (In Thousands)	478	441	460	465
Percent Change	-	-7.74%	-3.77%	-2.72%
Residential Building Permits (In Thous. Units)	157	156	133	123
Percent Change	-	-0.64%	-15.29%	-21.66%
Retail Trade Employment (In Thousands)	2771	2778	2787	2836
Percent Change	-	0.25%	0.58%	2.35%
Median Home Price (In Thousands)	$177.2	$182.2	$187.6	$200.6
Percent Chenge	-	2.82%	5.87%	13.21%
Manufecturing Employment (In Thousands)	1736	1755	1750	1758
Percent Change	-	1.09%	0.81%	1.27%

Figure 3. Economic projections for California for Q4, 1994 (percent changes vs. December 1993 forecast). Based on UCLA Business Forecasting Project.

Instead, insurance providers fear that another large quake on a major urban fault could devastate them financially. Statewide, insurers collect only about $500 million annually in premiums on all types of quake insurance, and their Northridge payouts have been several times that. Because California law requires that insurers offering residential property insurance must offer quake insurance as well and because rate increases can only be approved by the State's Insurance Commissioner, many large providers are not currently offering new policies. The *Sacramento Bee* notes, however, that rate hikes ranging from 37% to 208% have subsequently been approved by the Insurance Commissioner (December 12, 1994; p. J1).

The impact on California's housing market has clearly been negative but not necessarily large. The California Association of Realtors states that it has been more difficult to find insurance, consequently slowing down escrows and closings. But private insurance is still available, and the State Insurance Commissioner recently made the California's FAIR plan public insurance of last resort. Although there is anecdotal evidence of some housing purchases falling through due to the insurance situation, these are mostly the result of potential homeowners refusing to pay higher premiums. Housing permits are, in fact, 16% higher than in 1993.

Currently, California's housing market is performing relatively well. Offsetting allegedly negative ramifications of the state of the insurance industry and higher long-term interest rates on housing are higher consumer confidence and lower unemployment which are spurring new home buying. Even so, the potential for continued dampening in the housing market exists if affordable insurance cannot be made widely available.

CONCLUSION

The Northridge quake probably accelerated the onset of L.A.'s economic recovery by a few months. However, this came at a price – that recovery will be slightly less pronounced than if no quake had occurred.

The plethora of extreme predictions immediately following the quake–most since discredited–illustrate how the economic impacts of natural disasters are still not well-understood. Many commentators erred over both the *sign* of the quake's effect (i.e. whether it would be positive or negative) as well as the *magnitude* (i.e. whether it would be large or small).

It now appears that the quake caused a very brief disruption, followed by a surge in activity as a result of outside aid and rebuilding. Over the longer term economic activity will be slightly below the without-quake trend as residents pay for the initial rebuilding.

Thus, the quake was neither a boom or bust for Los Angeles. The quake's impact, in percentage terms, was bound to be modest in an area with an economy that is larger than all but a dozen countries.

The pessimists were confounded by a burgeoning economic recovery, and more importantly by the speed with which government responded with emergency aid and rebuilding, particularly of the freeways.

But the pessimists could have been right. The innovative and timely measures implemented by state and local agencies may well have made the difference between the Northridge quake's actual, modest effects and the economic tragedy that might have been.

REFERENCES

Association of Bay Area Governments, 1991, Macroeconomic effects of the Loma Prieta earthquake, November 1991.

DRI/McGraw Hill, 1994, Earthquake will hurt Los Angeles economy in the long run, January 21, 1994.

Dun & Bradstreet Information Services, 1994, The Los Angeles economy after the January 1994 earthquake, October, 1994.

EQE International, The Northridge, California, earthquake of January 17, 1994, undated.

Governor's Office of Planning and Research, 1994, Economic impact of the Northridge earthquake, February 1994.

Munroe, Tapan and Hoadley, Walter, The economic impact of the bay area earthquake of October 17, 1989, undated.

UCLA Business Forecast, 1994, The impact of the Northridge earthquake on the economies of California and Los Angeles, March 1994.

UCLA Business Forecast, The UCLA business forecast for the nation and California, various quarters.

The WEFA Group, 1994, U.S. Economic Outlook Special Report: The California earthquake, February 1994.

McCrink, T.P.,1995, Ridge-top landslides triggered by the Nothridge earthquake *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 273-278.

RIDGE-TOP LANDSLIDES TRIGGERED BY THE NORTHRIDGE EARTHQUAKE

by

Timothy P. McCrink[1]

ABSTRACT

Although the majority of the landslides triggered by the Northridge earthquake occurred in sparsely populated areas, a number of these failures were large and in areas that may be developed in the future, and therefore are of particular significance for the geologic community. A landslide which was triggered by the Northridge event along a ridge-top in the mountains near the town of Val Verde is described. Another landslide pre-dating the Northridge earthquake is shown to have many similarities to the recent one, suggesting that ridge-top landslides may not be unusual in this area. The purpose of this article is to describe this pair of ridge-top landslides and to suggest the idea, not yet proven, that landslides that displace the tops of ridges may be caused by seismic events.

NORTHRIDGE EARTHQUAKE LANDSLIDES

Within 30 hours of the Northridge earthquake, the California Division of Mines and Geology obtained high altitude U-2 photography from the U.S. Air Force to evaluate earthquake effects in southern California. Two geologists working with film positives and binocular microscopes analyzed this photography for surface rupture, liquefaction, and landslides caused by the earthquake. Through these efforts, coordinated with geologists in the field, a number of earthquake related ground failures were identified within a week of the earthquake. Earthquake-triggered landslides, with a few notable exceptions in the Sherman Oaks and Pacific Palisades areas, caused only minor damage in urbanized areas. However, a significant concentration of large, earthquake-induced landslides was recognized in the area north of the Santa Clara River and west of Interstate Highway 5, extending west to the vicinity of Lake Piru. Within the Val Verde 7 ½ minute USGS quadrangle at least eleven definite and five possible large earthquake-triggered landslides were recognized from the U-2 photography.

Several of these large earthquake-triggered landslides within the Val Verde quadrangle appear to be new; that is, although they may be associated with existing landslides, these failures occurred in previously intact bedrock. This article focuses on the largest of these new landslides, and one older landslide which, though not reactivated by the Northridge earthquake, shares many similar characteristics with the new one. These landslides are herein called the Del Valle landslide and the Old Del Valle landslide after the oil field on which they occur. The location of these landslides in relation to the Northridge earthquake epicenter is shown in Figure 1. Figure 2 shows the location of these landslides on a portion of a published geologic map (Dibblee, 1993). Photo 1 is an enlarged portion of a U-2 photograph showing both the Del Valle and the Old Del Valle landslides.

[1]California Department of Conservation, Division of Mines and Geology, Sacramento, California

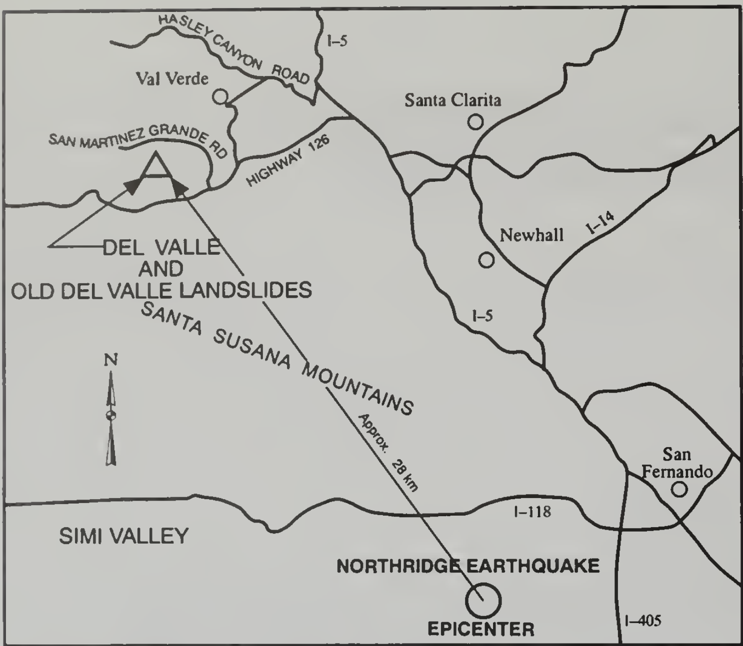


Figure 1. Location of the area of ridge-top failures relative to the epicenter of the Northridge earthquake.

Del Valle Landslide

The largest landslide triggered by the Northridge earthquake occurred on the ridge just north of the Santa Clara River and south of San Martinez Grande Canyon (Figure 2). The Del Valle landslide is a slump-block slide located approximately 20 km northwest of the earthquake epicenter. According to the geologic map for Val Verde quadrangle (Dibblee, 1993), the Del Valle landslide occurred in the Pico Formation, on the south limb of the Del Valle anticline with dips 17 to 30 degrees to the southeast. The Pico Formation is a Pliocene marine clastic sequence, described as a soft micaceous claystone and siltstone in the area of the Del Valle landslide (Dibblee, 1993). The landslide covers approximately 178,000 m^2 with the landslide mass moving from the top of the ridge down a south-facing dip slope.

Photo 1. Enlarged U-2 photo of Del Valle and Old Del Valle landslides. Photo courtesy of USAF-Beale AFB, 9th ISS.

Figure 2. Portion of Val Verde 7 1/2 minute geologic quadrangle map showing the locations of Del Valle and Old Del Valle landslides (from Dibblee, 1993).

Photo 2. Photo-mosaic of Del Valle landslide looking east. Photos taken one week after the Northridge earthquake. Santa Clarita is in the center background.

The top of the ridge failed during the formation of the Del Valle landslide and the main scarp extends into adjacent drainages to the north (Photo 1). The landslide mass moved to the south-southeast, with a series of uphill-facing minor scarps at a maximum distance of about 100 m to the south of the main scarp, forming a graben near the ridge top. The steeper slopes of the lower part of the landslide are hummocky, and show evidence of older shallow slope movement.

The Del Valle Landslide was field checked one week after the Northridge earthquake and several measurements were taken at that time. Photo 2, taken from a peak roughly 700 m west of the top of the landslide, shows the Del Valle landslide as it appeared then. The main scarp ranges up to 10 to 15 m in height. On the west flank, where an oil field access road was offset, 12 m of horizontal offset and 6 m of vertical offset were measured. If it is assumed that the surface displacement reflects the slide plane orientation, then the measured vertical and horizontal displacements would indicate a 26-degree slide plane inclination. This is consistent with the bedding attitudes, suggesting failure occurred along a bedding plane.

The east flank of the landslide is characterized by a zone of deformation and fissures, forming a northeasterly trending, 3 to 4 m high pressure ridge. The toe of the landslide occurs in colluvium at the top of a large, dormant rotational slump. This colluvium was observed in the field as a large bulge with numerous east-west trending compressional soil pop-ups or 'soil tents' which were at most about 10 to 20 cm high. It could not be determined in the field or from post-earthquake air photos whether the bulging ground at the toe of the landslide predated the earthquake, but the 'soil tents' appear to have preferentially formed on the colluvium bulge. The magnitude of the landslide displacement at the toe is only a fraction of that observed at the top of the landslide. During the field check no surface expressions of ground water were observed anywhere on the Del Valle landslide.

Old Del Valle Landslide

When the geologists at the Division of Mines and Geology performed their landslide analysis of the U-2 photography, the emphasis was on finding new or reactivated slope failures that could be attributed to the Northridge earthquake. Existing landslides were largely passed over if no evidence for reactivation could be found. However, during field visits to the Del Valle landslide it was recognized that an older ridge-top landslide existed immediately to the east of the Del Valle landslide. This landslide, the Old Del Valle landslide, pre-dates the Northridge earthquake and was not

Photo 3. Photo-mosaic of the 'top' of the Old Del Valle landslide looking east. Landslide movement was to the right.

reactivated by it. In the field, it appeared that the landslide movement was to the north, opposite that of the Del Valle landslide (Photo 3). However, on 1:12,000 scale aerial photos taken by the NASA–Ames Research Center five days after the earthquake, it was observed that this older landslide clearly moved toward the south-southeast. Photo 4 is a stereo pair of both the Del Valle and the Old Del Valle landslides and the morphology and direction of movement for these two landslides can be observed.

Like the Del Valle landslide, the Old Del Valle landslide occurred at the top of the ridge, in the Pico Formation, on the south limb of the Del Valle anticline. It also had displacement to the south-southeast, and extended into the adjacent drainage to the north. The Old Del Valle landslide, however, is more unusual moving a prominent ridge-line peak as a coherent block. Because the topography of the Old Del Valle landslide is subdued by erosion, it is difficult to estimate the magnitude of the displacement. However, it appears to be of the same magnitude (on the order of tens of meters) as the recent Del Valle landslide. Interpretation of the stereo air photos shows there may have been a larger component of rotational movement of this old landslide than that observed in the recent Del Valle landslide.

DISCUSSION

Recognizing the Del Valle landslide as an earthquake-triggered failure indicates that the potential for ridge-top failure needs to be considered in mapping landslide susceptibility for future earthquakes. Although this landslide occurred in an unpopulated area, it is likely that urban development within similar geologic conditions has occurred, or will occur, elsewhere in California.

The occurrence of the Del Valle and the Old Del Valle landslides raises other questions which have broader implications to seismic hazards and paleo-seismicity. The first and most important question is whether the ridge-top landslides described here require seismic shaking to be initiated. In a semi-arid area it seems difficult to have enough rainfall infiltration and subsequent ground water rise at the top of a ridge to create the conditions required to cause a large new landslide. Although a rainfall triggering mechanism has not been disproved, it is suggested here that the location of these landslides at the top of the ridge argues against such a mechanism, and suggests that these landslides may be a type of slope failure that can only be caused by earthquake shaking. A detailed subsurface investigation and stability analysis is necessary to prove or disprove this hypothesis.

Photo 4. Stereo pair air photos of the Del Valle and the Old Del Valle landslides, approximate scale 1:12,000. Photo courtesy of NASA-Ames Research Center, C-130 Program.

Another important question is whether ridge-top landslides occur in other parts of California or if they are unique to this area, or even to this particular ridge. The answer to this question will determine the level of significance that these landslides have to our understanding of seismic hazards. If they require an earthquake to trigger them, but they only occur in one place, then their significance is limited to gaining a greater understanding of the specific seismic events that caused them. If, on the other hand, a number of similar ridge-top landslides are known or can be recognized in other areas, there is the potential for using these landslides for age-dating past earthquakes through soil dating techniques, and to calibrate or refine pre-historic earthquake parameters by studying the dynamics of their displacement. This information would be significant to geologists and seismologists who are trying to model seismic sources for earthquake risk studies.

CONCLUSIONS

Two unusual landslides, one caused by the Northridge earthquake and one pre-dating it, have been identified in the mountains north of the Santa Clara River and briefly described here. These landslides share the following characteristics: (1) they occur at the top of a ridge rather than on the flanks; (2) they occur in relatively weak bedrock (Pico Formation) on the southern limb of a prominent anticline; (3) movement is in the direction of stratigraphic dip; and (4) the type of movement is slump-block sliding, with a significant component of translation, probably along bedding planes. The recognition of these characteristics will likely assist geologists in recognizing areas susceptible to this type of failure during future earthquakes.

The hypothesis has been presented here that these ridge-top landslides may require an earthquake to initiate them, which could provide an opportunity to use them to study the Northridge and perhaps earlier seismic events. If a definitive link to earthquake shaking can be established, and ridge-top landslides can be recognized in other areas of the state, we may have a tool to age-date past seismic events and to calibrate pre-historic earthquake shaking parameters.

REFERENCE

Dibblee, T.W., Jr., 1993, Geologic map of the Val Verde quadrangle, Los Angeles and Ventura Counties, California: Dibblee Geological Foundation Map No. DF-50, scale 1:24,000.

Greenwood, R.B.,1995, Characterizing blind thrust fault sources – an overview *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 279-287.

CHARACTERIZING BLIND THRUST FAULT SOURCES— AN OVERVIEW

by

Richard B. Greenwood[1]

INTRODUCTION

The January 17, 1994 earthquake and its aftershocks have highlighted the seismogenic significance of blind thrust faults and the importance of recognizing the strain contributions that these structures present to regional geologic syntheses. Although blind thrust faults do not exhibit primary surface rupture, they are not without surface expression. Growth-related hanging wall folds with coseismic activity are the most common indicators of blind thrust fault complexes. These structural complexes are most commonly recognized and characterized through a combination of oil well logs, seismic reflection records, and surface geologic mapping in conjunction with a number of other indirect indicators and interpretive methods, including kinematic and mass balance and models. Unlike faults that rupture the earth's surface, the recent seismogenic potential of blind thrust faults can only be characterized and evaluated by indirect means.

LOCATING BLIND THRUST FAULTS

Blind thrust faults are postulated on the basis of regional graphic reconstructions, earthquake focal mechanism solutions, and indications of coseismic folding including paleoseismic evidence, regional and local geodetic effects, and geomorphic features and their sedimentary influences.

1. Graphic reconstructions, including retrodeformable and kinematic reconstructions, and fault propagation and fault-bend fold models, when used in conjunction with seismicity, stratigraphy, and seismic data, provide a means of postulating the presence and character of blind thrust faults. Retrodeformable cross-sections are used by the petroleum industry and academia to geometrically and kinematically model rocks from a present deformed condition, back to a predeformed state (Dalstrom, 1969; Suppe, 1983; Woodward and others, 1985). Any resulting viable, but not unique, graphic solution is constrained in its regional context by fault slip rates, regional strain models, and late Quaternary sedimentation, as shown in Figure 1 (from Davis and others, 1989). Regional reconstructions that include blind thrust faults and their accompanying decollement surfaces provide a structural vehicle which accommodates late Pliocene and Quaternary shortening along low-angle surfaces, as first postulated by Yeats (1968).

Quantitative fault-bend fold concepts developed by Suppe (1983) and applied to the Los Angeles basin by Shaw and Suppe (1993, 1994) provide a graphical method of indirectly characterizing blind thrust fault ramps by modeling the hanging wall fold complexes and their influences on deposition. The model presumes that pre-existing decollement surfaces are joined by low to

[1]California Department of Conservation, Division of Mines and Geology, Southern California Regional Office, Los Angeles, California

moderately dipping thrust ramps. Continued movement on the decollement and thrust ramp surfaces results in seismicity and necessitates folding to conserve area in deformation. Folds are generated by kink band migration with axial surfaces which are pinned to the intersections between the decollement surfaces and the thrust ramp surface (fault bends). Continued fault movement widens kink-bands (fold limbs) that are bound by two axial surfaces-an active axial surface that is pinned to the fault bend and an inactive axial surface that moves with the hanging wall sheet, as shown in Figure 2 from Suppe and others, 1992. These kink-bands or fold limbs are commonly exposed at the surface or can be imaged in seismic reflection profiles, thereby approximating the position of the underlying, blind thrust fault. In areas of syntectonic deposition, kink-bands commonly narrow upwards, forming distinct growth triangles that approximate fault slip. In addition, the width between the translated inactive fold axes and the current active fold axis is directly related to the amount of fault dip-slip (Shaw and Suppe, 1993).

The Compton thrust ramp, beneath the Compton-Los Alamitos structural zone, was modeled by Shaw and Suppe (1993) as an addition to the conceptual Los Angeles basin model of Davis, Namson, and Yerkes, 1989. Upward narrowing kink-bands were imaged in high resolution seismic profiles, which led to a fault-bend fold model-defined thrust ramp. The addition of this model into balanced cross-sections was supported by high resolution reflection profiles, well logs, regional seismicity, surface geology, and by gravity modeling.

2. Seismology has been a useful tool in identifying the locations of blind thrust faults and accompanying structures. Seismologic data from large earthquakes, which provide a basis for immediate

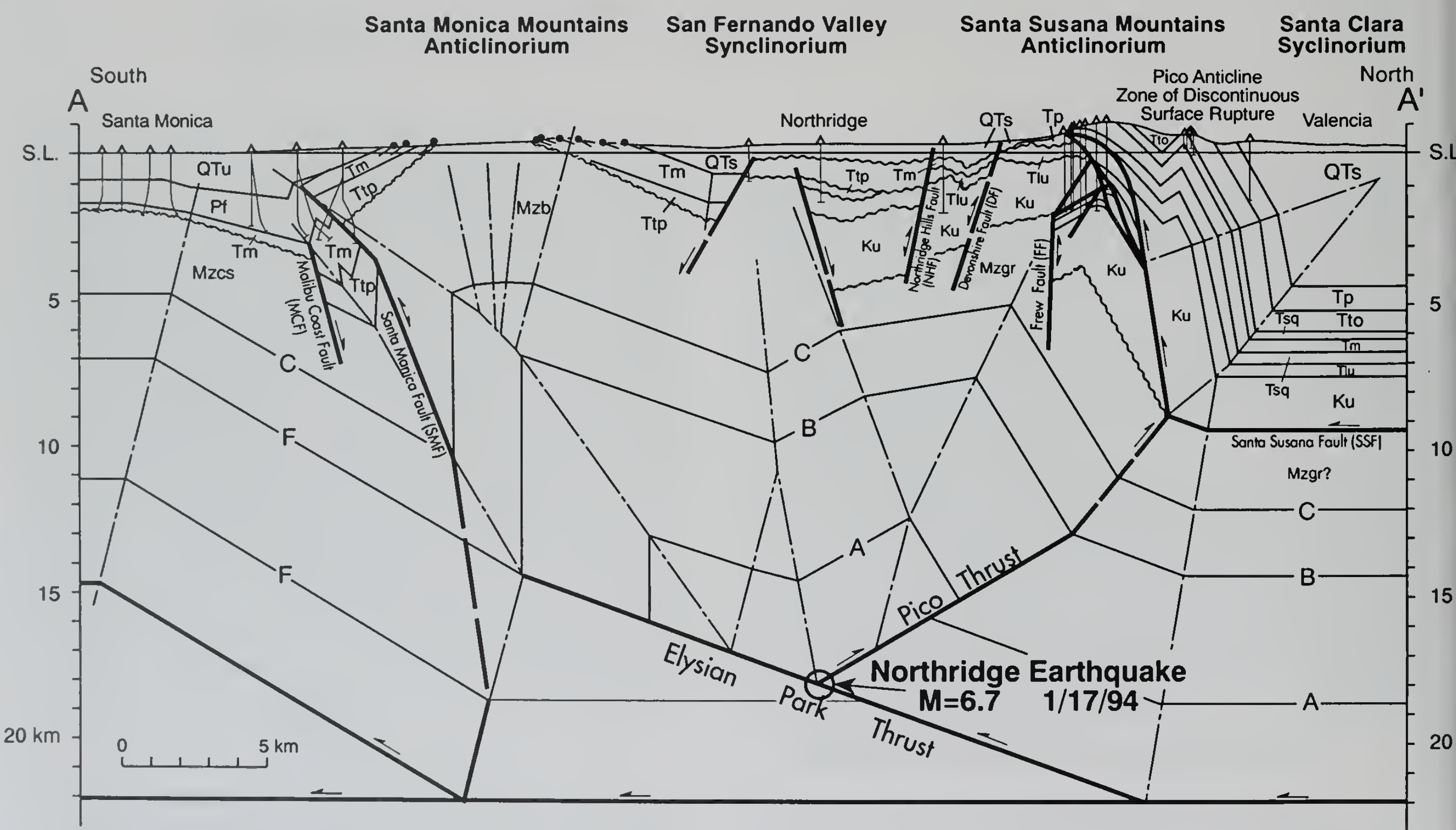


Figure 1. Balanced cross section across the portion of the Tansverse Range fold and thrust belt involved in the 1994 Northridge earthquake. Section shows structural interpretation of the origin of the 1994 Northridge earthquake and the convergent structure of the upper crust. Earthquake resulted from about 2 m of slip on the Pico thrust which is interpreted to be a backthrust to the Elysian Park thrust. The Santa Susana Mountains and Santa Monica Mountains anticloria are interpreted to be crustal scale fault-propogation folds above the Pico and Elysian Park thrusts, respectively. In this minimum slip solution the Pico thrust has 2.3 km of total slip and the Elysian Park thrust has 11.8 km of total slip. The initiation of the Santa Susana Mountains anticlinorium and the Pico thrust is recorded by deformation of the youngest unit, the Saugus Formation, which is no older than 2.3 ma (Levi and Yeats, 1993). The slip and age yield a minimum slip rate of 1.0 mm/yr. for the Pico thrust. The Santa Monica Mountains aniclinorium initiated between 2-3 ma (Davis, Namson and Yerkes, 1989) and the slip and age range yield a slip rate for the Elysian Park thrust from 3.9-5.9 mm/yr. Used by permission; Davis, Namson Consultants, Southern California Earthquake Center, 1994 report, unpublished.

modeling of mainshock and aftershock depths and focal mechanisms, are collected through instrumentation nets maintained by the California Division of Mines and Geology, the United States Geological Survey, the California Institute of Technology, University of Southern California, and numerous other universities. Modeling of main event and aftershock seismic data to define focal depth and focal mechanisms, the absence of primary surface rupture, and context with postulated regional shortening models have provided a basis for defining blind thrust causative mechanisms for larger earthquakes at Coalinga, Whittier Narrows, and Northridge.

Seismic data from smaller earthquakes, when placed in the context of surface and subsurface geologic information, has also provided a basis for modeling blind thrust faults. Hauksson (1990) recognized that the spatial association of earthquake focal mechanisms of (M>2.5), rather than epicenters, provide consistent and compelling correlations with locations of late Quaternary faults and folds. This approach has provided a basis for defining and segmenting blind thrust faults in the Elysian Park and Torrance-Wilmington fold and thrust belts.

EXPLANATION

South of Santa Monica Mountains

Qtu	Undifferentiated upper Fernando Fm and younger Quaternary units
QTs	Saugus Fm
Pf	Lower Fernando Fm
Tm	Undifferentiated Modelo and Puente Fms
Ttp	Topanga Fm and lower Teriary units
Mzcs	Catalina Schist
— C — — B — — A —	Form lines showing late Cenozoic convergent structure in the crystalline basement rocks

North of Santa Monica Mountains and Western San Fernando Valley

QTs	Saugus Fm
Tp	Pico Fm
Tto	Towsley Fm
Tsq	Sisquoc Shale
Tm	Monterey Shale
Tlu	Undifferentiated lower Tertiary units
Ku	Upper Cretaceous strata
Mzgr	Granitic rocks
Mzb	Santa Monica slate and other metamorphic and granitic rocks of the Santa Monica Mtns.
— C — — B — — A —	Form lines showing late Cenozoic convergent structure in the crystalline basement rocks

3. Paleoseismologic-based reconstructions recognize that, although blind thrust faults lack primary surface rupture, their past history of activity can be indirectly derived by investigating their secondary structures associated with coseismic hanging-wall fold development. Surficial methods of investigation, commonly utilized on faults with surface rupture, including trenching and dating disturbed soil horizons and soil development rates, are also appropriate for examining fold-related bedding plane faults and bending-moment faults (Cotton and others, 1990). Bending-moment faults result from tensional-normal stress on the convex side of a folded layer and compressional stress on the concave side of the fold (Yeats, 1986).

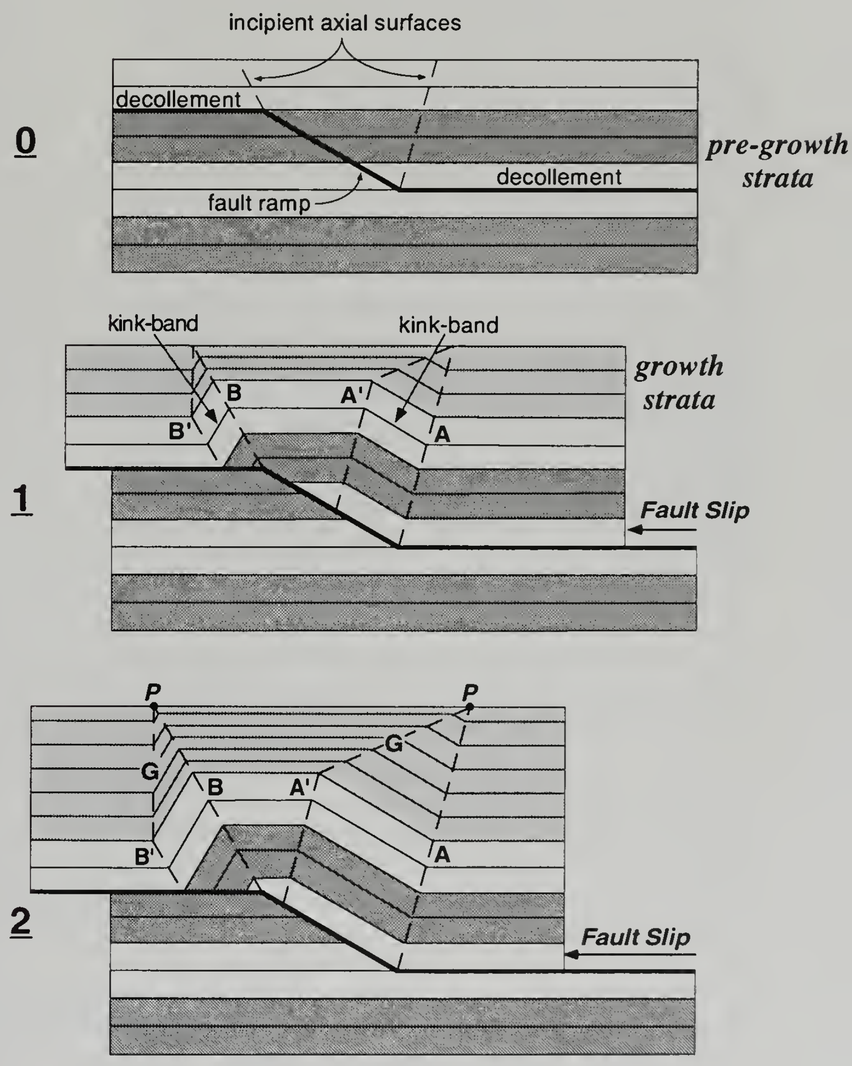


Figure 2. Progressive development of a fault-bend fold (from Suppe, Bischke, and Shaw, 1992. 0: An incipient thrust ramp connecting two decollement fault segments in pregrowth strata. 1: Fault slip causes folding of the hangingwall block along active axial surfaces (A and B) that are pinned to the two fault bends. Inactive axial surfaces (A' and B') form at fault bends and are rigidly translated away from active axial surfaces by slip. 2: Progressive fault slip widens both kink-bands, which narrow upward into syntectonic (growth) strata. Inactive axial surfaces in growth strata are labeled G; points of surface folding are labeled P. Used by permission; Suppe and others, 1992.

4. Geodetic-controlled reconstructions, which use the measurement of the earth's surface, provide a means of characterizing crustal deformation and defining regional strain models by using satellite-based Global Positioning Systems (GPS) data (Donnellan, and others, 1993; Feigl and others, 1993). These regional strain models provide broad reference frames for comparing local crustal deflection, attributed to coseismic folding. Coseismic elevation changes, measured by land-based leveling, provide additional constraints in postulating fault-fold model dimensions and orientations. These geometric solutions assist in correlating mainshock depth with focal mechanisms, and locations of initial aftershocks (Lin and Stein, 1989; Stein and Ekstrom, 1992).

5. Geomorphic features, generated by uplift and deformation of blind thrust hanging wall sediments, provide an indirect basis from which blind thrust occurrence can be inferred. The most obvious geomorphic indication of blind thrust faults is the presence of coseismic anticlinal hanging- wall growth folds. The concept of fault-rooted folds has provided structural models which explain the occurrence of hills in the New Idria - Coalinga - Kettleman Hills -Lost Hills areas of Central California (Namson and Davis, 1988) and the Elysian and Montebello Hills of east Los Angeles. These fault-fold models are spatially consistent with the seismologic evidence commonly associated with blind thrust faults: deep focal depths, shallow-dipping focal mechanisms, and dispersed aftershocks, as evidenced in the New Idria-Coalinga-Kettleman Hills earthquakes (Stein and Ekstrom, 1992), and the Whittier Narrows earthquake (Hauksson and Jones, 1989). Noting the coincidence between clusters of aftershocks and fold locations, Stein and Ekstrom (1992) inferred that fold bends and fold offsets overlie lateral or tear faults between adjacent blind thrust ramps, which provided a basis for blind thrust segmentation.

Local growth folds associated with blind-thrust faults that lack obvious surface expressions can often be imaged by seismic reflection profiles and modeled to define underlying blind thrust faults (Suppe, Bischke, and Shaw, 1992; Shaw and Suppe, 1993). Local growth folds can also be indirectly identified through recognition of basin asymmetry, deposition of syntectonic sediments, and uplift of fluvial and marine terraces (Davis and others, 1989). Additional indicators of fold development are the subtle effects of uplift, tilting, and warping on local stream gradients, which result in changes in fluvial terrace longitudinal profiles, changes in stream gradients and drainage sinuosity, and increases in depth of stream incision. These criteria, in conjunction with soil development rates and assuming an absence of nontectonic influences, have been used to define rates of uplift in the Elysian Park anticlinorium (Bullard and Lettis, 1993). Through fault-fold modeling (Shaw and Suppe, 1993) fold uplift rates can yield modeled slip rates on underlying blind thrust ramps, or at least can be used to constrain fault and slip rate modeling.

PRELIMINARY CHARACTERIZATION OF BLIND THRUST SEISMIC POTENTIAL

The seismogenic potential of blind thrust faults in the Los Angeles basin has only recently been recognized after the 1987 Whittier Narrows earthquake and the 1994 Northridge earthquakes.

The "earthquake potential," the likelihood of a fault generating a damaging event in the future (Yerkes, 1985), as evaluated from the perspective of seismic moment, seismicity, and slip rate (Brune, 1968), is especially difficult to determine on faults that do not break the earth's surface. Traditional surficial methods combine seismicity with surface mapping and trenching to define maximum fault rupture dimensions and geometry, fault segmentation, and paleoseismic information which lead to estimates of slip rates and recurrence intervals. The equivalent blind thrust fault physical parameters can only be modeled or defined by indirect measurements. Also important are assumptions regarding strain release through aseismic deformation mechanisms including aseismic fault creep and ductile deformation at depth.

Accumulated Seismic Moment

Seismic moment stored on a fault is partially released with each earthquake. Considering earthquakes in the Los Angeles basin since 1800, Hauksson (1992) used the concept of accumulated seismic moment (CSM_o) from Brune (1968) to characterize the potential seismic hazard presented by blind thrust faults in the Elysian Park and the Torrance-Wilmington fold and thrust belts:

$$CSM_o = \mu Ast.$$

In this formula, μ is the shear modulus, A is the modeled fault area undergoing slip, s is the fault slip rate, and t is the time interval. The Elysian Park fold and thrust belt extends 100 km through at least five segments, and the Torrance-Wilmington extends 60 km through at least three segments (Davis and others, 1989; and Hauksson, 1990). Both structural belts have postulated average depths of 10 km (Hauksson, 1992). The slip rates of major faults were derived from balanced cross-sections (Davis and others, 1989). Any of these eight fault segments could yield a M>5 to M>6.7 earthquake. If several segments could rupture simultaneously a M>6.7 to M>7.8 earthquake could occur (Hauksson, 1992). From the perspective of cumulative seismic moment released in earthquakes since 1800 on faults in the Los Angeles

basin, Hauksson (1992) concludes that almost twice the seismic moment is currently (prior to the Northridge earthquake) stored on concealed faults, compared to surface faults.

Measured Coseismic Uplift

Uplift attributed to coseismic folding can also be used to evaluate seismic potential of blind thrust ramps. Uplift measurements can become a constraining parameter in modeling fault plane dimensions and orientation from main shock and aftershock data. A fault plane solution, combined with slip rates that are acceptable in the context of retrodeformable cross sections (Davis and others, 1989), leads to an estimate of earthquake recurrence intervals and an estimate of potential seismic moment and seismic moment released, from which the potential seismic hazard on blind thrust ramps can be evaluated (Lin and Stein, 1989). This approach was illustrated by a fault plane solution modeled for the 1987 Whittier Narrows earthquake by Lin and Stein, (1989). A plane was defined based on mainshock modeling of focal depth, focal mechanism, anf fault plane geometry. The plane also passed through the majority of radiating initial aftershock locations, and met the constraint of 50 mm modeled surficial deflection through coseismic folding. Fault plane parameters of length, width, dip, depth of burial, and azimuth of the east end of the upper fault edge were modeled to estimate smallest and largest fault plane surfaces and their respective minimum and maximum seismic moments. These modeled geodetic moments can be compared for concordance against seismic moments estimated from teleseismic amplitudes, short and long period body waveform data and regional broadband recordings (Lin and Stein, 1989). The estimated geodetic moment can also be compared with seismic moments associated with slip rates derived from regional uplift models (Davis and others, 1989) to define an estimated deficit in moment release, which is used to evaluate seismic potential of this blind thrust fault ramp.

Indirectly-Derived Coseismic Uplift

The seismic potential of blind thrust faults can be indirectly constrained by relating the deformation of Quaternary deposits and geomorphic surfaces to the uplift associated with coseismic folding. By comparing the pattern, amount, and rate of Quaternary deformation with the patterns and locations of Tertiary deformation, sequential fault-fold growth models can be developed.

These fold growth rate models have been applied to give an indirect assessment of the seismic potential of the blind thrust ramp underlying the Monterey Park and Montebello Hills, within the Elysian Park anticlinorium (Bullard and Lettis, 1993). Areas of uplift, tilting and warping were highlighted by range crest profiles (revealing water gaps), longitudinal stream profiles (which revealed subtle gradient changes associated with uplift), drainage net maps and detailed topographic residual maps (which highlight amounts and patterns of fluvial incision), and regional slope maps. Rates of geomorphologic changes were constrained by mapping Quaternary fluvial units with recognizable degrees of soil development. Maximum rates of uplift of 0.1 mm/yr to 0.25 mm/yr were defined which could be used to constrain the segmentation, depth, and dimensions of fault-fold geometric models (Bullard and Lettis, 1993).

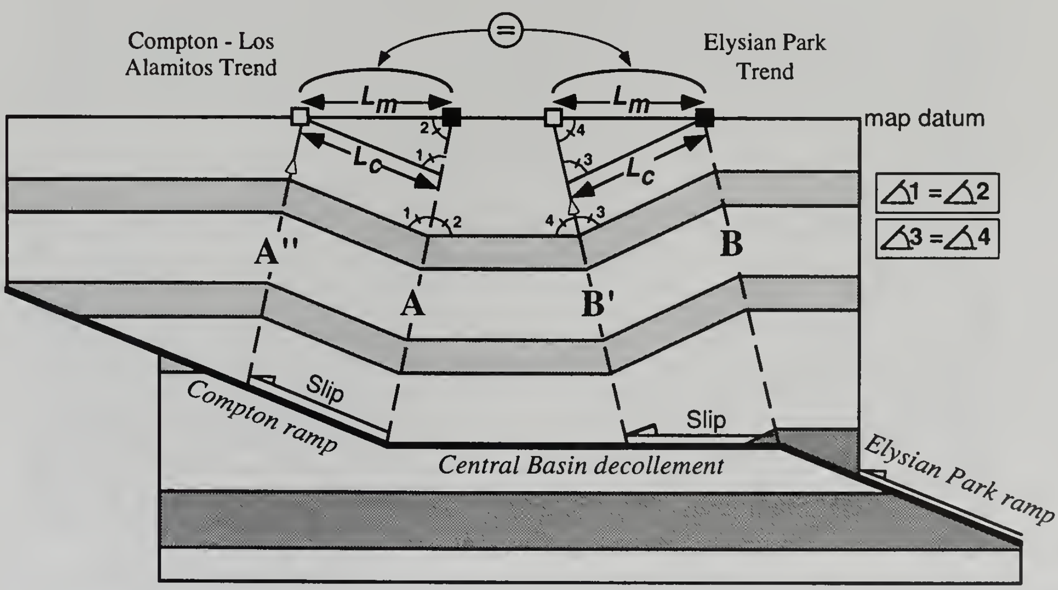


Figure 3. Diagram showing axial surface mapping technique, relation between kink band widths and fault slip, and relation between Compton ramp and part of the Elysian Park thrust system. Used by permission; Shaw and Suppe 1993; Shaw and Suppe (in press).

Characterization by Axial Fold Maps

The seismic potential of blind thrust faults can also be characterized by mapping axial fold surfaces which geometrically infer fold size, fold shape, fault geometry, and slip distribution of the underlying fault ramp segments from which potential magnitudes and recurrence intervals can be estimated (Shaw and Suppe, 1993; Shaw, Hook, and Suppe, 1994; Shaw and Suppe, in press). Axial planes can be mapped at the surface from geologic exposures or from seismic reflection profiles, (as illustrated in Figures 3 and 4 from Shaw and Suppe, in press) where axial surfaces are projected from depth. The lateral extent of axial surfaces reveals the extent and size of underlying blind-thrust ramps, because the folds are presumed to be structually linked to the fault bends. Discontinuities of mapped axial surfaces identify possible structural offsets along lateral or oblique faults, which provide a basis for segmentation of blind thrust faults.

The earthquake potential of an active blind thrust can be estimated by using fault (or ramp) segment sizes (Figure 5, from Shaw and Suppe, in press) in conjunction with empirical relationships between the modeled fault rupture area (RA in km^2), moment magnitude (M),

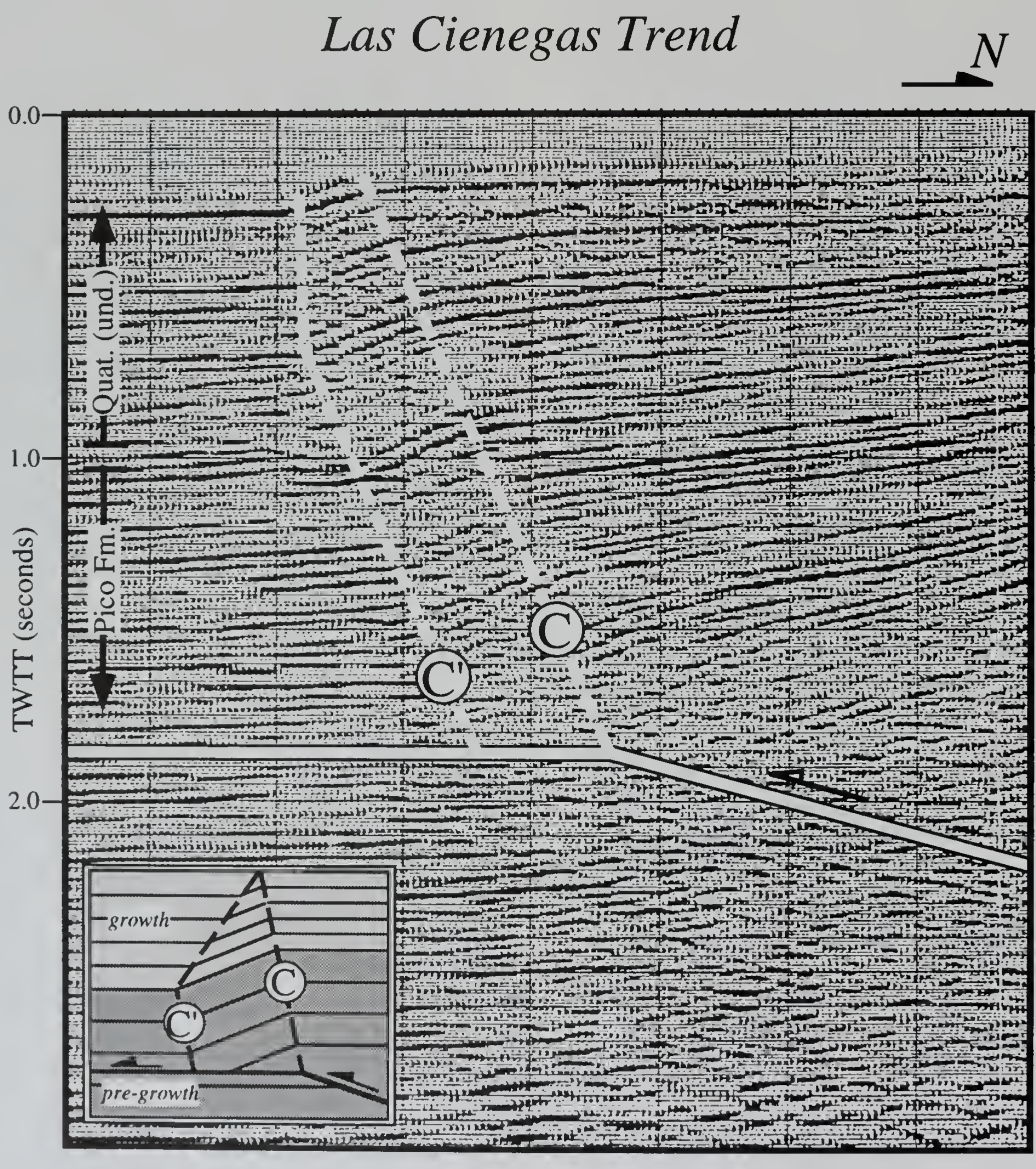


Figure 4. Seismic record illustrating a narrowing upward kink band, or growth triangle, along the southwestern side of the Elysian Park trend, located near the Los Angeles River. The fold shape is consistent with flattening of a shallow fault ramp (Las Cienegas blind thrust) to a horizontal decollement in the central Los Angeles basin (*left*). The inflection in the axial surface C' marks the initiation of faulting in the Quaternary. Used by permission; Shaw and Suppe, 1993; Shaw and Suppe, in press.

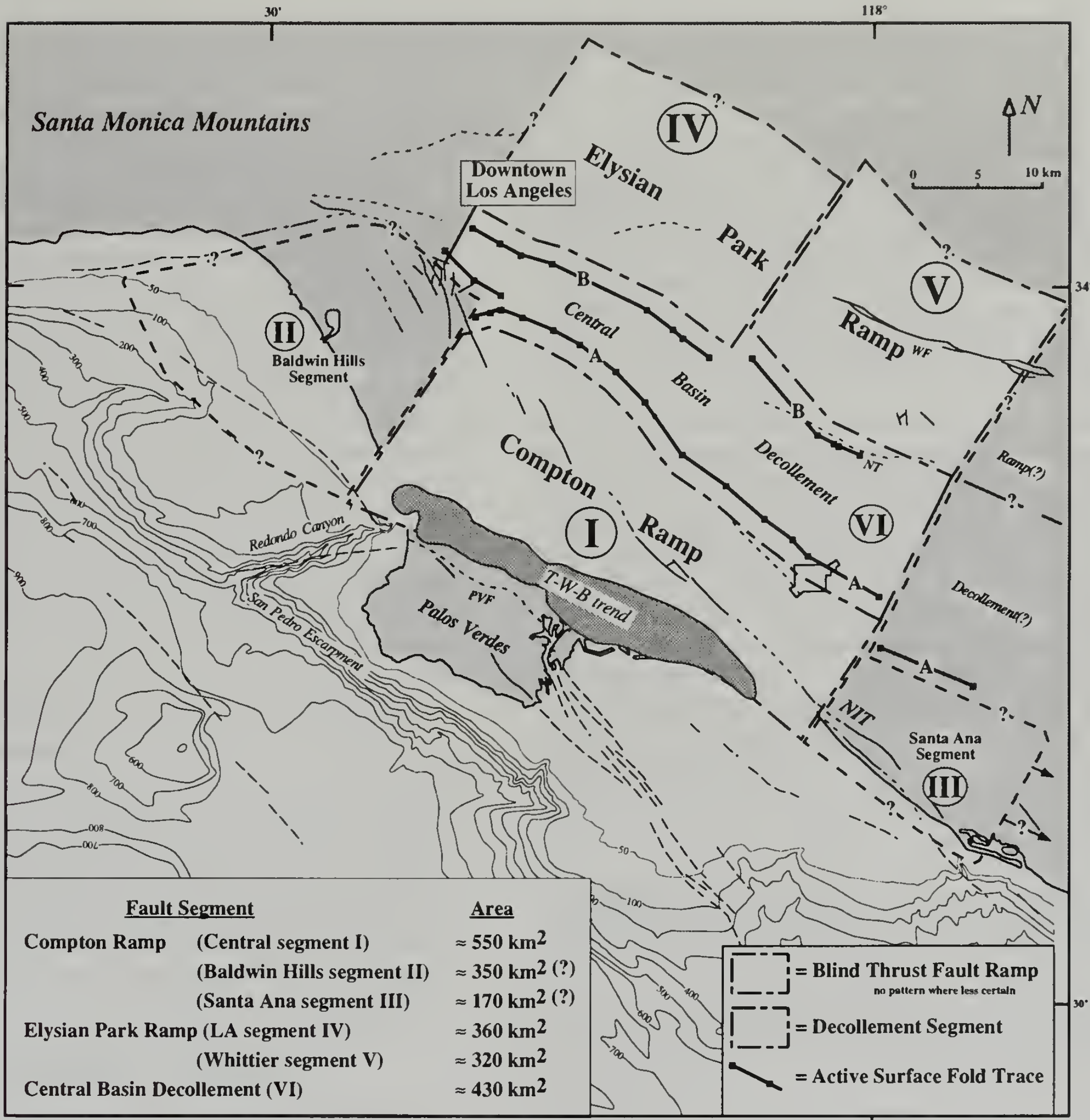


Figure 5. Map of segments of the Compton and Elysian Park blind-thrust ramps, Central Basin decollement, and overlying fold trends. Fold trends: (A) Compton-Los Alamitos trend; (B) Elysian Park trend; (T-W-B) Torrance-Wilmington-Belmont trend. Offsets in map-view of the Compton - Los Alamitos and Elysian Park trends overlie potential segment boundaries of the underlying Compton and Elysian Park ramps. The Compton ramp consists of a Central segment (I) and adjacent Baldwin Hills (II) and Santa Ana (III) segments. The Elysian Park ramp consists of the Los Angeles (IV) and Whittier (V) segments, and is separated from the Compton ramp by the Central Basin decollement (VI). Used by permission; Modified from Shaw and Suppe, 1993; Shaw and Suppe, in press.

average coseismic displacement (AD in meters) to derive possible recurrence intervals (RI in years) and long term slip rate (LTS in meters/year) as presented in Wells and Coppersmith (1994) for thrust and reverse faults:

$$M = 4.28 + 0.92 (\log RA)$$

$$M = 6.96 + 0.81 (\log AD)$$

$$RI = AD/LTS$$

Then recurrence intervals can be estimated by

$$M = 6.96 + 0.81 (\log RI \bullet LTS).$$

Application of this approach by Shaw and Suppe (in press) on the Central Compton ramp of the Compton - Los Alamitos structural trend yields possible moment magnitudes of M = 6.3 to 7.1 (including multi-segment rupture scenarios) with a slip rate of approximately 1.4 mm/year and a recurrence interval of about 450 years, considering coseismic slip of 0.6 meters. These authors note that a possible recurrence interval of 850 to 2100 years is possible for M ~6.8 earthquakes with 1.5 to 3.0m coseismic slip. They also note that larger segment ruptures are plausible if the Compton thrust ramp extends beneath the Santa Monica thrust front and/or southeast

to Newport-Mesa. Similar scenarios by Shaw and Suppe (in press) for the Elysian Park ramp (Figure 4) yield possible moment magnitudes of M = 6.6 for the Los Angeles and Whittier segments (or M ~ 6.9 for simultaneous rupture of both segments), with an approximate slip rate of 1.7 mm/year, and possible recurrence interval of 200 and 230 years, respectively. Additional scenarios by these same authors also consider joint rupture of the Elysian Park ramp, the Compton Ramp and its possible extensions, and the intervening Central Basin Decollement.

Slip rates and recurrence intervals can also be approximated by placing growth fold geometry in the broader context of regional kinematically-balanced cross-sections (Davis and others, 1989, and Dolan and others, 1995). Shaw and Suppe (in press) note that the multitude of possible blind thrust earthquake scenarios can be strengthened by additional constraining geologic data. They also state that more dated events, improved age constraints of folded Quaternary sediments, and estimates of coseismic uplift across kink bands would identify characteristic rupture cycles, quantify coseismic slip, suggest ramp segments that may have ruptured simultaneously, and improve resolution of slip rate estimates and recurrence intervals.

SEISMIC HAZARD MAPPING STUDIES IN PROGRESS—PRESENT APPLICATIONS

The preliminary damage estimates of $13 to $15 billion (Stewart and others, 1994) from the January 17, 1994 Northridge earthquake and its attributed blind thrust source (Hauksson and others, 1994) underscore the importance of understanding the mechanics and processes of blind thrust fault development. A survey by the California Seismic Safety Commission (1994) of present research reveals that most efforts to regionally characterize blind thrust seismic hazards are being funded and conducted by the Southern California Earthquake Center, the United States Geological Survey, and by numerous universities and independent researchers through funding by the National Earthquake Hazards Reduction Program (NEHRP), as detailed in Jacobson (1992, 1993).

Efforts to remap fold belts in the Los Angeles basin using retrodeformable cross sections and compressional focal mechanisms, which resulted in the definition of the Torrance-Wilmington fold and thrust belt (Davis and others, 1989; Hauksson, 1990), are continuing. Similar efforts are continuing in the Montebello Hills, central Los Angeles basin, and the Puente Hills/eastern Los Angeles basin. This continuing research recognizes that the blind thrust fault responsible for the 1987 Whittier Narrows earthquake (Davis, and others, 1989; Hauksson, 1990) is likely part of a much larger and complexly segmented system of folds and thrusts which comprise the Elysian Park fold and thrust belt (Davis and Namson, 1992). Further resolution of the Compton and Elysian Park structural belts (Shaw and Suppe, 1993) by means of axial fold mapping continues to be funded by NEHRP.

Efforts to model the recent Northridge earthquake data include applications of balanced cross-sections, surface geology, and oil company data as a basis for defining a causitive blind thrust fault under the San Fernando Valley that is related to development of the adjacent Santa Clara synclinorium (Davis and Namson, 1994). A contrasting model supported by aftershock focal mechanisms assigns the causitive fault to an eastward continuation of the Oak Ridge Fault from the adjacent Ventura basin (Yeats and Huftile, 1995).

ACKNOWLEDGMENTS

Review comments were gratefully received from Thom Davis (Davis and Namson, Valencia, California), Roy Kroll (Zeiser Geotechnical, Costa Mesa, California), John Shaw (Texaco Exploration Research, Houston, Texas), and Russ Miller and Mark Peterson, Division of Mines and Geology.

REFERENCES

Brune, J.N., 1968, Seismic moment, seismicity, and rate of slip along major fault zones: Journal of Geophysical Research, v. 73, p.173-182.

Bullard, T.F., and Lettis, W.R., 1993, Quaternary fold deformation associated with blind thrust faulting, Los Angeles basin, California: Journal of Geophysical Research, v. 98, no. B5,p. 8349-8369.

California Seismic Safety Commission, 1994, Report on the Northridge earthquake: Executive Order Report W-78-94, p. G1-G21.

Cotton, W.R., Fowler, W.L., Van Velsor, J.E., 1990, Coseismic bedding plane faults and ground fissures associated with the Loma Prieta earthquake of 17 October 1989, *in* McNutt, S.R., and Sydnor, R.H., 1990, The Loma Prieta (Santa Cruz Mountains), California, Earthquake of 17 October 1989: California Division of Mines and Geology Special Publication 104, p. 95-102.

Dahlstrom, C.D.A., 1969, Balanced cross sections: Canadian Journal of Earth Sciences, v. 6, p. 743-757.

Davis, T.L., and Namson, J.S., 1992, Characterization and seismic potential of blind thrusts along the northern margin of the Los Angeles basin: U.S. Geological Survey Open File Report 92-258, p. 234-235.

Davis, T.L., and Namson, J.S., 1994, A balanced cross section of the 1994 Northridge earthquake, southern California: Nature, v. 372, no. 6502, p. 167-169.

Davis, T.L., Namson, J.S., and Yerkes, R.F., 1989, A cross-section of the Los Angeles area – Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard: Journal of Geophysical Research, v. 94, no. B7, p. 9644-9664.

Dolan, J.F., Sieh, K., Rockwell, T.K., Yeats, R.S., Shaw, J., Suppe, J., Huftile, G.J., and Gath, E.M., 1995, Prospects for larger or more frequeant earthquakes in the Los Angeles Metropolitan region: Science, v. 267, p. 199-213.

Donnellan, A., Hager, B.H., King, R.W., and Herring, T.A., 1993, Geodetic measurement of deformation in the Ventura basin region, southern California: Journal of Geophysical Research, v. 98, no. B12, p. 21,727-21,739.

Feigl, K.L., Agnew, D.C., Bock, Y., Dong, D., Donnellan, A., Hager, B.H., Herring, T.A., Jackson, D.D., Jordan, T.H., King, R.W., Larsen, S., Larson, K.M., Murray, M.H., Shen, Z., and Webb, F.H., 1993, Space geodetic measurement of crustal deformation in central and southern California, 1984-1992: Journal of Geophysical Research, v. 98, no. B12, p. 21,677-21,712.

Hauksson, E., 1990, Earthquakes, faulting, and stress in the Los Angeles basin: Journal of Geophysical Research, v. 95, no. B10, p. 15,365-15,394.

Hauksson, E., 1992, Seismicity, faults, and earthquake potential in Los Angeles, southern California *in* Pipkin, B.W. and Proctor, R.J., eds., 1992, Engineering geology practice in southern California: Association of Engineering Geologists, Southern California Section, Special Publication, no. 4, p. 167-179.

Hauksson, E. and Jones, L.M., 1989, The 1987 Whittier Narrows earthquake sequence in Los Angeles, southern California: Seismological and tectonic analysis: Journal of Geophysical Research, v. 94, p. 9569-9590.

Hauksson, E., Hutton, K., Kanamori, H., Jones, L., Mori, J., 1994, The Mw 6.7 Northridge, California earthquake of January 17, 1994 and its aftershocks (abstract): Seismological Society of America, 89th annual meeting.

Jacobson, M.L., compiler, 1992, National Earthquake Hazards Reduction Program, summaries of technical reports volume XXXIII: United States Geological Survey Open-File Report 92-258, 1019 p.

Jacobson, M.L., compiler, 1993, National Earthquake Hazards Reduction Program, summaries of technical reports volume XXXIV: United States Geological Survey Open-File Report 93-195, 983 p.

Levi, S., and Yeats, R.S., 1993, Paleomagnetic constraints on the initiation of uplift on the Santa Susana Fault, western Transverse Ranges: Tectonics, v. 12, no. 3, p. 688-702.

Lin, J.S., and Stein, R.S., 1989, Coseismic folding, earthquake recurrence, and the 1987 source mechanism at Whittier Narrows, Los Angeles basin, California: Journal of Geophysical Research, v. 94, no. B7, p. 9614-9632.

Namson, J.S., and Davis, T.L., 1988, Seismicallly active fold and thrust belt in the San Joaquin Valley, central California: Geological Society of America Bulletin, v. 100, p. 257-273.

Shaw, J.H., Hook, S.C., and Suppe, J., 1994, Structural trend analysis by axial surface mapping: American Association of Petroleum Geologists Bulletin, v. 78, no. 5, p. 700-721.

Shaw, J.H., and Suppe, J., 1993, Earthquake hazards of active blind-thrust ramps in the Los Angeles basin, California *in* Shaw, J.H., ed., Active blind-thrust faulting and strike-slip fault-bend folding in California: Princeton University PhD. thesis, 216 p.

Shaw, J.H., and Suppe, J., 1994, Active faulting and growth folding in the eastern Santa Barbara Channel, California: Geological Society of America Bulletin, v. 106, no. 5, p. 607-626.

Shaw, J.H., and Suppe, J., in press, Earthquake hazards at active blind-thrust faults under the central Los Angeles basin, California: Journal of Geophysical Research, 44 p.

Stein, R.S., and Ekstrom, G., 1992, Seismicity and geometry of a 110-km-long blind thrust fault 2. Synthesis of the 1982-1985 earthquake sequence: Journal of Geophysical Research, v. 97, no. B4, p. 4865-4883.

Stewart, J.P., Bray, J.D., Seed, R.B., and Sitar, N., eds., 1994, Preliminary report on the principal geotechnical aspects of the January 17, 1994 Northridge earthquake: Earthquake Engineering Research Center, University of California at Berkeley, Report no. 94/08, 245 p.

Suppe, J., 1983, Geometry and kinematics of fault bend folding: American Journal of Science, v. 283, p. 684-721.

Suppe, J., Bischke, R.E., and Shaw, J.H., 1992, Regional map-view and cross-sectional determination of fault geometry and slip for blind thrusts in populated areas of southern California: Southern California Earthquake Center 1992 Report; Annual Meeting, Los Angeles, California, p. C37.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of Seismological Society of America, v. 84, no. 4, p. 974-1002.

Woodward, N.B., Boyer, S.E., and Suppe, J., 1985, An outline of balanced cross sections: Department of Geological Sciences Publication 11, University of Tennessee, Knoxville, 170 p.

Yeats, R.S., 1968, Rifting and rafting in the southern California borderlands *in* Dickinson, W.R., and Grantz, A., eds., Proceedings of conference on geologic problems of San Andreas Fault system: Stanford University Publications, p. 307-322.

Yeats, R.S., 1986, Active faults related to folding: Active Tectonics: National Academy Press, Washington, D. C., p. 63-79.

Yeats, R.S., and Huftile, G.J., 1995, The Oak Ridge fault system and the 1994 Northridge earthquake: Nature, v. 373, p. 418-420.

Yerkes, R.F., 1985, Geologic and seismologic setting *in* Ziony, J.I., ed., Evaluating earthquake hazards in the Los Angeles Region – an earth science perspective: United States Geological Survey Professional Paper 1360, p. 25-41.

Ranous, R., 1995, Code implications and issues for commercial, industrial and residential buildings *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 289-290.

CODE IMPLICATIONS AND ISSUES FOR COMMERCIAL, INDUSTRIAL, AND RESIDENTIAL BUILDINGS

by

Richard Ranous[1]

Looking at the results of the safety assessment process (see article on page 195, this volume) we see that 79 percent (90,311) of the buildings evaluated had no life-threatening damage, 10 percent (11,483) of the buildings had some form of life-threatening damage that needed to be addressed before long-term occupancy could be permitted, and only 3 percent (2,998) of the buildings had damage of such a life-threatening nature that they could not be entered until the damage was repaired. The remaining 8 percent (9,123) of the buildings were in an unknown condition and, as previously stated, a large percentage of those would fall in the INSPECTED (green) category. If we combine these statistics with the fact that only a small percentage of the 59 deaths resulting from the earthquake can be directly attributable to building damage, we can say that the building code did as it was intended to do. That is, the code minimized the risk of loss of life to the occupants and therefore, served its intended purpose. An argument could certainly be made that, based on the Northridge earthquake, wholesale change of the building code is not necessary.

Any change in the acceptable level of risk associated with the building code must come from the public. If there is to be such a change, it will come in criteria building owners place on their architects and engineers when designing their buildings. This is where performance based standards will play an important role. Once developed, a potential building owner will be able to choose the level of performance that they want from their building. Basically, the level would vary from code minimum life-safety protection to having the building fully functional and operational following an earthquake.

Case studies that have been completed and are currently underway and comments from those involved in the safety assessment process indicate that one of the major issues that needs to be addressed is quality control. At a minimum, one could say that some of the damage was a direct result of the quality of the design of the building, the quality of the construction, or both. This is an issue which has been and still is a point of discussion in code development. The results of the Northridge earthquake will only add to those discussions.

There are some issues that can be specifically addressed by changes or enhancements to the building codes. A significant need exists to develop retrofit standards for older forms of construction. Within the City of Los Angeles, for example, the Northridge earthquake has led to the adoption of retrofit standards for pre-1973 tilt-up buildings as well as voluntary retrofit standards for single-family residences. Additionally, voluntary single-family retrofit standards have been submitted to the International Conference of Building Officials for inclusion as Appendix Chapter 5 of the Uniform Code for Building Conservation. The City of Los Angeles standards are based on these generic standards modified to be specific to Los Angeles.

[1] Office of Emergency Services, Southern California Earthquake Preparedness Project, Pasadena, California.

From a specific material or system standpoint there are some potential changes to the code or additional standards that need to be discussed, addressed, or developed. Some of these include:

- Ductility standards for interior columns not a part of the lateral force resisting system.
- Standards for hillside residential construction
- More testing of stucco as a material for use in the lateral force resisting system of buildings
- Reduction and/or elimination of allowable shear values for questionable sheathing materials such as stucco and drywall.
- Requirement for wider shear panels in conventional construction requirements for single-family residences.
- Retrofit standards for apartment buildings with parking areas under the buildings resulting in soft stories.
- Revisions to design criteria for steel moment frame buildings.

As with past earthquake disasters, the Northridge earthquake reinforced the need for uniform repair standards. Repair standards have been left up to the individual jurisdictions to develop and adopt through their ordinance process. As we began the recovery phase of this disaster, OES and FEMA developed a Memorandum of Understanding which established minimum levels of repairs that would be eligible for federal funding under Public Assistance. These standards were based on the concept of comparing cost to repair to cost to replace. “Triggers” for levels of repair where developed based on these percentages and incorporated mitigation of the causes of the damage. This approach has been proposed to the International Conference of Building Officials for inclusion in the Uniform Building Code as a minimum repair criteria. If adopted, this places a minimum repair criteria in the code which can then be modified by a jurisdiction through ordinance. Having such a criteria in the code will simply reduce the pressure for local government to rapidly develop specific repair standards.

Pandya, S., 1995, Code implications and issues for hospitals *in* Woods, Mary C., and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 291.

CODE IMPLICATIONS AND ISSUES FOR HOSPITALS

by

Sharad Pandya[1]

GENERAL

Currently the building code for the structural design of hospital buildings consists of the 1991 Edition of Uniform Building Code with 1992 State of California Amendments (Code). The following code related and other issues arise from the observations of structural damage in the Northridge earthquake.

Design Base Shear

The Northridge earthquake, on a buried thrust fault, generated very high values of horizontal and vertical ground accelerations in the free field. Several steel moment frame buildings sustained fractures at the joints. Due to these observations it is necessary to reevaluate (1) the code required design base shear to resist earthquakes, and (2) the methods of designing and constructing steel moment frame buildings.

Penthouses

Requirements for the structural design of penthouses (equipment/storage sheds) at the roof level of hospitals and the anchorage of equipment installed therein should be reconsidered.

Non-structural Equipment and Systems

Both pre-1973 and post-1973 hospitals sustained damage to piping and equipment. Code requirements and enforcement for these should be reconsidered.

Pre-1973 Hospitals

These buildings are at a greater risk of being damaged in earthquakes than are post-1973 buildings. Senate Bill 1953, signed into law by Governor Pete Wilson on September 21, 1994, provides the legal and technical framework for the mitigation of that risk.

[1]Office of Statewide Health Planning and Development, Sacramento, California.

Yashinsky, Mark, 1995, Code issues for seismic safety of bridges *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 293-297.

CODE ISSUES FOR SEISMIC SAFETY OF BRIDGES

by

Mark Yashinsky[1]

INTRODUCTION

Changes to the Caltrans seismic bridge code may come from Caltrans continuing research program, from bridge engineers developing better analyses procedures, seismic designs and retrofit strategies, or from geotechnical engineers and seismologists developing more realistic earthquake forces. However, all of this work is stimulated by careful studies of bridge damage after powerful earthquakes. Not only does this give engineers an understanding of how existing bridge designs perform, but it gives insight into where new research should be directed. For instance, Caltrans has long been interested in the performance of flared columns during earthquakes. However, actual damage during the Northridge earthquake provided the impetus for Caltrans to continue research on flared columns. Thus, a cyclical push over test of flared columns, better analysis procedures for flared columns, and a study of how to improve the architectural features of columns began, in part, because of the Northridge earthquake.

After the 1971 San Fernando earthquake, and at the direction of the Federal Highway Administration (FHWA), the Applied Technology Council (ATC) formed a group to look at seismic bridge specifications and recommend changes to improve bridge safety during earthquakes. These recommendations are commonly referred to as ATC 6. They were studied by engineers and many of the recommendations were adopted nationally and by Caltrans. After the 1989 Loma Prieta earthquake, Caltrans funded the ATC to study Caltrans specifications and design procedures and to propose new changes. This is known as the ATC 32 Project. However, the work of the ATC 32 Committee has not been completed. Lessons learned from the Northridge earthquake will no doubt be incorporated into the ATC 32 document.

Also, after the Loma Prieta earthquake, the governor recommended the establishment of a Seismic Advisory Board made up of scientists and engineers outside of Caltrans to provide input into the Caltrans current seismic design procedure. The establishment of criteria for two levels of design for important bridges, a safety evaluation using the maximum credible earthquake, and a serviceability evaluation using a smaller, probability based earthquake, came from recommendations of this Board.

The basis of Caltrans *Bridge Design Specifications* is the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Bridges. However, other criteria were added by Caltrans that reflects the much larger and more frequent earthquakes that devastate California. This includes higher response spectra, a map of California giving peak ground accelerations, and methods for determining the demands and capacities of bridge members for earthquakes. Not all seismic code requirements find their way into *Bridge Design Specifications*. Recommended seismic practice is also outlined in *Memos to Designers*. For instance, recommendations for seismic retrofit design and joint shear requirements are in Memos to Designers Section 20-4. Chapter 14 of *Bridge Design Aids* includes instructions for modeling bridges for seismic analysis, instructions for designing earthquake restrainers, minimum hinge seat widths for earthquakes, and other earthquake information. Other earthquake requirements are not put into a manual but are incorporated into computer programs used by designers. Procedures for obtaining spring stiffnesses for foundations, for modeling the nonlinear behavior of bridge foundations, and obtaining the displacement capacity of columns, beams, and frames are found in various computer programs.

[1]California Department of Transportation, Office of Earthquake Engineering, Sacramento, California

Thus, proposed changes to Caltrans seismic bridge code may come from many sources, may be reviewed by several groups, and may end up in a variety of media. However, the impetus for most new criteria comes from large earthquakes such as the Northridge earthquake. These earthquakes are the final arbiters of Caltrans seismic codes and procedures.

AREAS OF STUDY

The Northridge earthquake validated much of Caltrans' current seismic procedures. In particular, current retrofit strategies performed very well during the Northridge earthquake. However, the Northridge earthquake also provided some new areas of concern and new ideas for retrofit and new bridge design. Some of these ideas Caltrans has been dealing with for a while. Others have shifted in importance due to the earthquake. Still other ideas Caltrans is just beginning to consider. In the last 20 years Caltrans made a major effort to provide sufficient ductility to bridge members. Now the Northridge earthquake has put an emphasis on understanding bridge system behavior, the effect of vertical accelerations on bridges, and some problems with skews and other geometric issues. The following are proposed design revisions developed by Caltrans design and seismic engineering staff. It should be understood that the final revisions may differ significantly from these proposals.

Balancing Member Stiffnesses

Much effort was spent on this issue after the Northridge earthquake. In particular, the original structures on the 5/14 Interchange had problems with stiff columns adjacent to more flexible columns attracting very large forces. It was necessary to make sure that problem was not repeated in the replacement structures. What makes this difficult, is that length plays such a significant role in column stiffness ($k=L^3/nEI.$). This problem was solved for the 5/14 interchange by varying the length and width of columns with drilled shaft foundations and using 'isolation casings' to give the columns more equal stiffness (Figure 1).

Another method was used to balance column stiffnesses on the Alemany Interchange Retrofit Project. In that project, isolation bearings were placed on stiff columns to change substructure stiffness and maintain a similar response between columns.

In general this problem is being addressed with the following proposals:

(1) Keep all column stiffnesses in a frame within a certain percent of each other. Keep all column stiffnesses in a bent within a certain percent of each other.

(2) Use isolators or sliding bearings on stiff columns next to an abutment.

(3) Develop procedures for determining effective moments of inertia for columns during earthquakes.

(4) Make a better determination of actual column stiffness by studying the as-build condition of the bridge. This would include consideration of superelevations, type of pin or moment connection, differences in soil stiffness, column flare and other architectural elements, and location of curbs, barriers, and other nonstructural elements.

(5) This issue goes hand in hand with establishing ductility levels on a bridge. If stiff columns are unavoidable at a location, then higher ductilities must be used to handle the increased demand at that location.

(6) Use Type Selection Meetings to discuss these issues and to develop strategies for maintaining similar flexibilities throughout the structure.

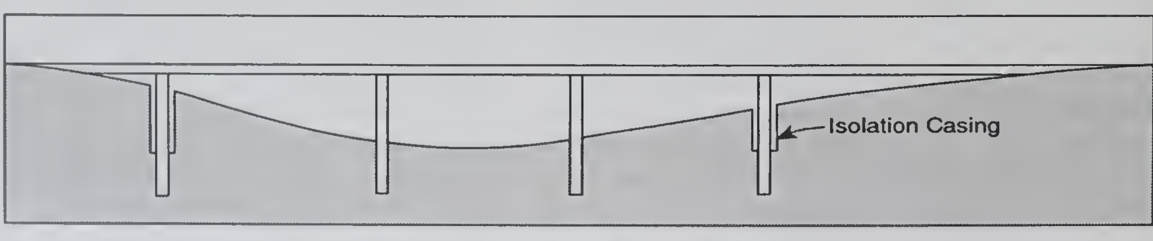


Figure 1. Maintaining constant column stiffness by using special 'isolation casings'.

Vertical Ground Motions

High levels of vertical acceleration were recorded during the Northridge earthquake. This was in a frequency range that could excite structures to ductilities of 2 or higher. The high vertical acceleration usually was accompanied with very large horizontal shaking. This high vertical acceleration appears to be related to the near field behavior of thrust faults. Since blind thrust faults may be a problem for California, it may be prudent to develop some criteria to deal with them. A vertical response spectra was used for the replacement of the 5/14 Connector overcrossing Bridge #53-2795G (Figure 2). This vertical response spectra has a maximum acceleration of 1.8 g for short periods between 0.1 to 0.35 seconds. It is an envelope of five vertical acceleration records obtained during the Northridge earthquake. No decision has been made so far on including this type of response spectra in a future bridge code. Caltrans recommended that engineers working on the 5/14 Interchange Replacement Project also design the superstructure for a vertical force of 1.5 g in an upward direction and 0.5 g in a downward direction. Moments and shears for this loading were combined with moments and shears for an unfactored dead load and compared to all other loading cases. The superstructure was designed for the critical loads. End conditions were carefully considered so that if a bridge had a seat type abutment, the end condition would be a cantilever for the upward direction. However, tiedowns should probably be provided where uplift is a problem. The moment capacity of columns would also be much lower as the axial load becomes smaller. Areas that are especially vulnerable for vertical loads would be Outriggers, C-Bents and very long spans. The end result of all of this was the addition of a nominal amount of mild steel being placed in the soffit near the supports and the top deck at midspan for superstructure moments caused by upward vertical loads. Other areas that should be examined are the bent cap to superstructure connection, girder stirrups, and bearing devices. It is proposed to have an additional Group VII load case as shown below:

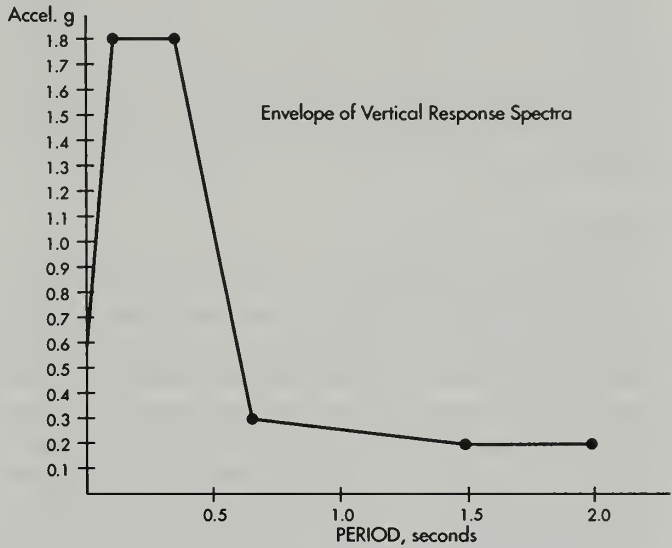


Figure 2. Vertical response spectra used for 5/14 Connector Overcrossing column flares.

Proposed EQ Load Case 3 = 1.0(DL) + 1.0(Vert. ARS) + 0.3(Long. ARS) + 0.3(Trans. ARS)

Column Flares

Column flares were an area of concern before the Northridge earthquake although no damage had at that time occurred due to flares. The problem was that engineers had long assumed that the flare was a non-structural element that would spall off during an earthquake. In reality, the flare was reducing the length of the column and increasing the plastic shear demand. A 2-inch gap between the soffit and the flare was one solution used to address these problems (Figure 3). However, testing at the University of California at San Diego showed that a 2-inch gap was too small and caused a high strain in the longitudinal steel. A three-prong approach is being used to address this problem. The first is to develop a simple procedure for designers to use to determine the plastic moment, shear, and hinge location for flared columns. This would require considering different plastic hinge locations on the flare. The plastic hinge will form at the location

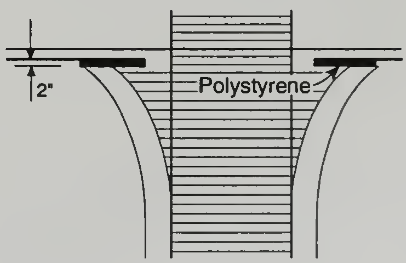


Figure 3. Former column flare.

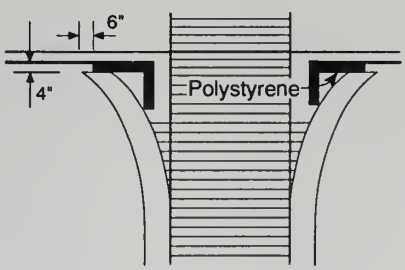


Figure 4. Improved column flare.

that results in the smallest plastic shear. A second approach is a research project to test different flared columns and validate their behavior. The third step is to come up with better flared column details. Figure 4 shows one proposed flare detail. A research project at the University of California at San Diego on Architectural Concrete and Bridge Columns is also developing architectural details that improve the seismic performance of columns. Alternatively, Caltrans architects are evaluating ornamental facades for bridges using nonstructural material that should not affect bridge behavior during earthquakes.

Skews

Highly skewed bridges can cause problems during earthquakes. Skewed bridges are extremely weak for one direction of rotation. In Figure 5, the abutments of the skewed bridge are very stiff in the counterclockwise direction but have very little stiffness in the clockwise direction. This clockwise rotation will cause the superstructure to slide out of its abutment seat. Also the columns of skewed bridges experience more biaxial bending during earthquakes. Finally, there is some question as to how effectively the current modeling procedure for bridges captures skew behavior. Possibly using *two* beam members or a grid to represent the superstructure would give more realistic displacements and forces for earthquake loads. This is the recommendation of the new load and resistance factor design of the American Association of State Highway and Transportation Officials Specifications currently under review. Certainly the partial collapse of the Gavin Canyon Bridges shows a need for better analysis techniques for skewed bridges. Whenever possible, skew should be eliminated or made as small as possible. Seat type abutments and hinges should

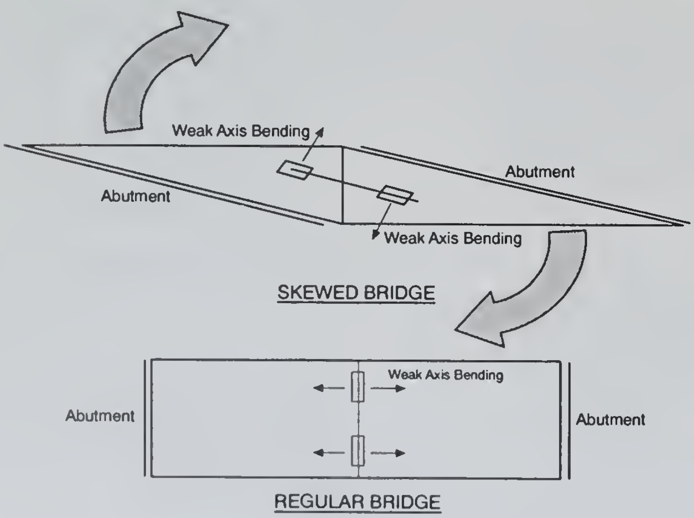


Figure 5. Skewed bridge behavior.

be avoided or provided with much larger seats for bridges with high skews. Bridges with abutment skews in opposite directions (Figure 6) like Mission Gothic Undercrossing should be avoided since they are extremely weak in one direction of movement.

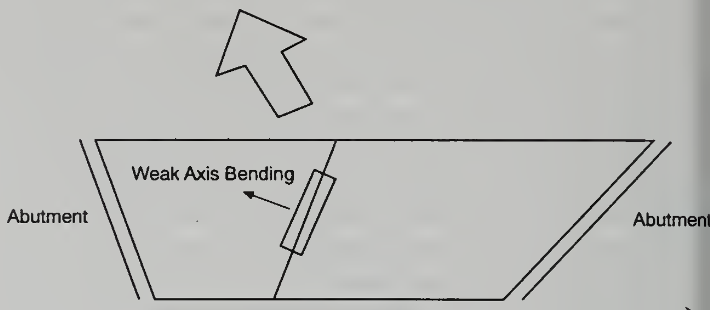


Figure 6. Weak direction movement of opposite skewed bridges.

Improved Abutment Design

Very flexible abutments allow more of the earthquake force to go to the columns. Seat type abutments may have contributed to bridge damage at several locations during the Northridge earthquake. For many years, Caltrans has discouraged using end diaphragm abutments due to a history of maintenance problems. Since the Loma Prieta earthquake, retrofits that attach large diameter cast in drilled hole piles to abutments to give them added strength, stiffness, and ductility have been used. A proposed new abutment design improves on this pile retrofit concept. This new design separates the lateral load supports from the vertical load supports of the abutment. The goal is for the large pileshafts to take the lateral force leaving the abutment wall undamaged. The design provides about 12 inches of pileshaft movement before the backwall is engaged. This new abutment design was used on the replacement bridges at the 5/14 Interchange.

Improved Hinges

The phase 1 retrofit program began after the 1971 San Fernando earthquake to prevent large hinge movements with cable and rod restrainers. These retrofits had some success in controlling large movements during the Northridge earthquake. But the current hinge design makes it extremely difficult to make repairs and replace damaged bearings. Newer, more repairable hinge details are being developed. A new expansion joint design provides much better seismic response with no danger of unseating (Figure 7). This new design was used on a replacement bridge in the 5/14 Interchange. This hinge may be particularly appropriate at locations where large displacements are expected.

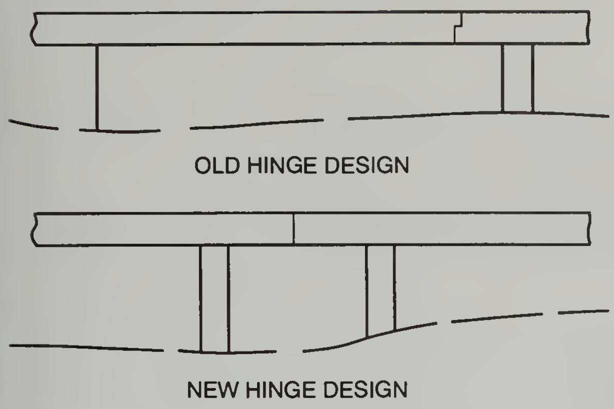


Figure 7. Old and new hinges

Other Issues

There are many other issues related to bridge analysis and design that the Northridge earthquake has raised. Issues relating to superstructure design such as cap to superstructure connections, flexural reinforcement for prestressed bridges, and superstructure joint shear are being examined. Research into earthquake force issues such as faulting, site specific response spectra, and near field events is ongoing. Other code related issues include hinge restrainers, pier walls, bent caps, footings, piles, and ductility factors.

CONCLUSIONS

Since the 1971 San Fernando earthquake, the seismic safety of bridges has been a high priority, including funding research to answer many of the questions raised by Northridge and other earthquakes in making bridges safer during earthquakes. As soon as research is completed on any of the issues discussed in this report, Caltrans shares that information with its engineering staff. Ciasses, informal discussions, workshops, papers and phone calls go back and forth between researchers and engineering staff to improve the safety of new and retrofit bridge design. This allows Caltrans to test new ideas in actual practice to see if they are practical. Peer Review Panels and Caltrans' Seismic Advisory Board carefully monitor decisions, seismic retrofits, and new bridge designs. Before any bridge is built, a type selection meeting is held with participation from The Office of Earthquake Engineering to make sure that the latest criteria is being used and that the general plan reflects a safe seismic design. All seismic retrofits must go through a similar strategy meeting where the analysis and final retrofit are closely examined.

A new improved code and design procedure is gradually taking shape through work by researchers, the ATC32 Committee, and with input from Caltrans engineers and the Seismic Advisory Board. Thus, new designs and retrofits will take advantage of the lessons learned from Northridge and the other earthquakes that Caltrans has carefully studied both in California and around the world.

Chittenden, Robert, 1995, Code implications and Issues for welded/bolted steel special moment frame buildings *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 299.

CODE IMPLICATIONS AND ISSUES FOR WELDED/BOLTED STEEL SPECIAL MOMENT FRAME BUILDINGS

by

Robert Chittenden[1]

The typical prescribed beam-to-column connection as set forth in Section 2710(g)1B of the 1991 Uniform Building Code (UBC) was found to be damaged in 120 steel Special Moment Resisting Frame buildings after the 1994 Northridge earthquake. This pattern of structural damage involving the brittle failures of beam-to-column connections in steel Special Moment Resisting Frames [SMRF'S] was unexpected (see article on page 147, this volume). This unexpected damage has shaken structural engineers' confidence in the predictability of the performance of steel Special Moment Resisting Frames and the reliability of conventional welded flange/bolted web steel beam-to-column connections as prescribed by the Uniform Building Code.

As a result of the magnitude of the problem with the prescriptive connection, the International Conference of Building Officials (ICBO), upon petition by the Structural Engineers Association of California (SEAOC) and the California Seismic Safety Commission, took the unprecedented step of prohibiting the prescriptive joint by way of an emergency code change in the 1994 Uniform Building Code. Similarly, the California Building Standards Commission has adopted an emergency code change in the 1992 California Building Code prohibiting use of the prescriptive connection for school, hospitals, state owned essential services buildings, and other state buildings. The code changes were written in performance oriented language rather than prescriptive terms. The reason for this is that there is insufficient knowledge currently available to write prescriptive language. The performance language allows for changing interpretation as more data becomes available without requiring another code change.

Both codes still allow for design and construction of steel Special Moment Resisting Frames. However, the code changes adopted require that the design consider the effects of overstrength and strain hardening. Also, the connection must have sufficient inelastic rotation capacity to exceed the demand for the application. The engineer must basically demonstrate by an approved cyclic test that the connection to be used will meet or exceed the strength and inelastic rotation criteria. The code changes also allow for substantiation by approved calculation. Substantiation of inelastic rotation capability by calculation is virtually impossible, hence the need for testing. As more and more testing becomes available, the engineer can then qualify the connection by comparison to existing tests by calculation.

Because the performance oriented code language does not define quantitatively the terms overstrength, strain hardening, or inelastic rotation capability, nor does the language define "approved" cyclic tests or calculations, the various professional organizations and users will publish guidelines and Interpretation of Regulations. SEAOC has put forth an initial interim guideline and will publish a more definitive final guideline. Similarly, the SAC Joint Venture will publish guidelines upon completion of testing. The Division of State Architect and the Office of Statewide Planning and Development will publish an Interpretation of Regulations. All these documents will be updated as more data becomes available.

[1]Division of State Architect, Office of Regulation Services, Sacramento, California

Mulqueen, S.P., and Hebein, J.J., 1995, Oilfield conditions and natural hydrocarbon seepages - effects of the Northridge earthquake *in* Woods, Mary C. and Seiple, W. Ray, eds., The Northridge, California, Earthquake of 17 January 1994: California Department of Conservation, Division of Mines and Geology Special Publication 116, p. 301-302.

OILFIELD CONDITIONS AND NATURAL HYDROCARBON SEEPAGES - EFFECTS OF THE NORTHRIDGE EARTHQUAKE

by

Stephen P. Mulqueen[1] and Jeffrey J. Hebein[2]

VENTURA BASIN

The earthquake which occurred on the morning of January 17, 1994, caused major damage to the oil fields in northern Los Angeles and Ventura Counties. Nineteen oil fields reported damage to facilities including pipeline breaks, tank ruptures, lease road failures, power outages, and one confirmed downhole wellbore failure.

Aliso Canyon oil field, closest to the epicenter, is primarily a gas storage field operated by Southern California Gas Company. Immediately after the earthquake, all gas withdrawal operations were shut down pending an assessment of damage to facilities and to the wells (Photos 1 and 2). Temperature surveys were conducted on approximately 80 percent of the wells in the field to determine if any downhole wellbore damage occurred. Downhole damage was only found on well "Standard Sesnon" 4-0 in which the 7-inch casing was mechanically parted at a depth of approximately 1400 feet.

Twenty-eight oil fields experienced a decrease in oil and gas production as a result of either inoperable production facilities or inaccessibility to sales lines. Immediately after the earthquake some wells in the Placerita oil field experienced an increase in total fluid production, but have since returned to pre-earthquake levels. Minor decreases in hydrocarbon production were observed in the Aliso Canyon and nearby Oat Mountain oil fields.

Increased natural seep activity was observed in Los Angeles, Ventura, and Santa Barbara Counties (Photo 3). New seeps have been reported in the Ojai and Newhall oil fields. However, this may not be an effect of the seismic activity, as seeps usually become more active in warmer and/or wetter weather.

Photo 1. Landslide damage to pipelines at Aliso Canyon oil field from the Northridge earthquake. Photos by S.P. Mulqueen.

[1]California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, Ventura, California
[2]California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, Long Beach, California

Photo 2. Surface damage to a well site in Aliso Canyon oil field from the Northridge earthquake.

Former and present oil seepages and near-surface hydrocarbon migrations are common occurrences around the Los Angeles basin's numerous oil and gas reservoirs. The Whittier, Rosecrans, Chino-Soquel, Sansinena, Brea-Olinda, Newport, Los Angeles City, and Salt Lake oil fields have exhibited periodic surface seepages. Such seepages and shallow migrations commonly occur near alluvial disruptions (for example, Salt Lake oil field) or specific permeable, faulted, stratigraphic units that outcrop at the ground surface (as at Brea-Olinda and Los Angeles City oil fields).

Alluvial disruption (slumping and cracking) over bedrock faulting is a prime mechanism for the older and newly-occurring surface seepages, especially in the Rancho La Brea Tar Pits location. New hydrocarbon seepage activity has occurred in the Los Angeles basin since the Northridge tectonic (seismic) event. Most notable are the new seepages around the Rancho La Brea Tar Pits extrusion site. The Salt Lake oil field regime is probably the area with the most prominent seepage from an underlying hydrocarbon reservoir/overlying rock-alluvium capping environment to be found within California oilfield areas.

Outside of oil fields, numerous oil/gas seepages have occurred in the Los Angeles basin. Some fluid intrusions have occurred in basements of buildings. Seepage can occur wherever permeable, oil-impregnated rock outcrops and/or where alluvium is present overlying such rock.

LOS ANGELES BASIN

Within the Los Angeles basin, no reports of oil/gas wellbore shear-offs in either the shallow alluvial sections or the deeper reservoir rock sections of the Los Angeles basin were received after the Northridge tectonic event.

Prior to the Northridge event, the Los Angeles City oil field's production was somewhat stable. Immediately thereafter oil and water production increased by as much as one-third, with anomalously high gas production in some wells. One well's production actually quadrupled. Hydrocarbon production has dropped somewhat, but still averages higher than pre-earthquake rates. Plausible explanations for these dramatic increases are reservoir refracturing/permeability rejuvenations and/or tectonic fluid and rock pressure increases.

Photo 3. A new oil seep appeared at Ojai field after the Northridge earthquake.